ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

The CERN Accelerator School

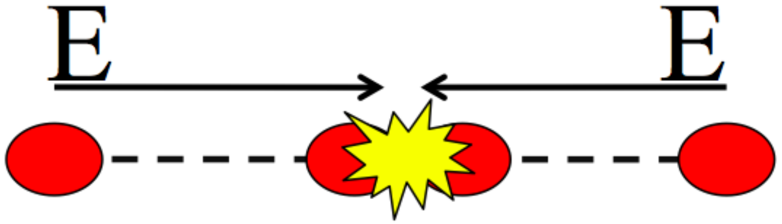
Beam-Beam Effects

Tatiana Pieloni
Laboratory of Particle Accelerator Physics
EPF Lausanne

CERN Advanced Accelerator Physics School 2017
Royal Holloway University of London

Colliders

$$E^* \approx 2 \times E$$



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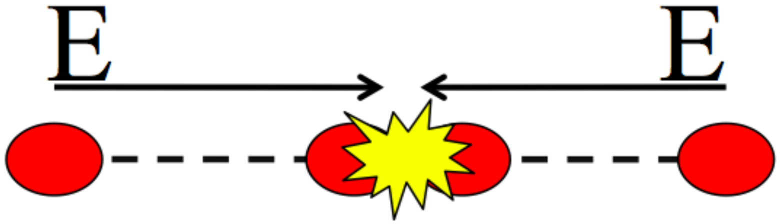
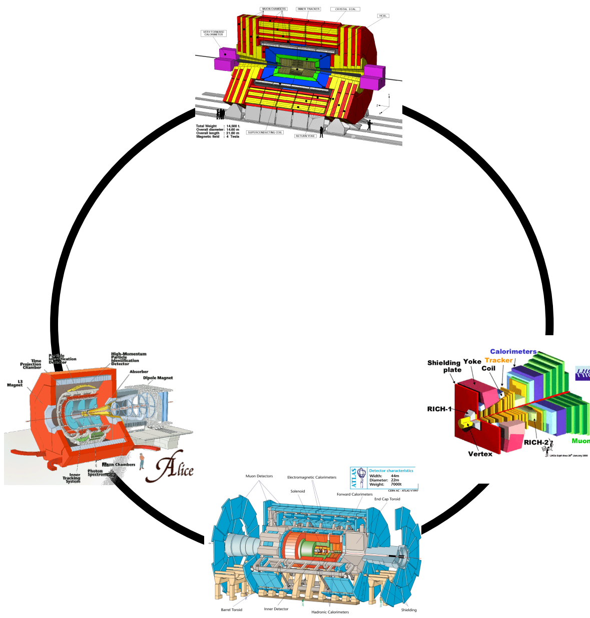
$$N_{event/s} = L \cdot \sigma_{event}$$





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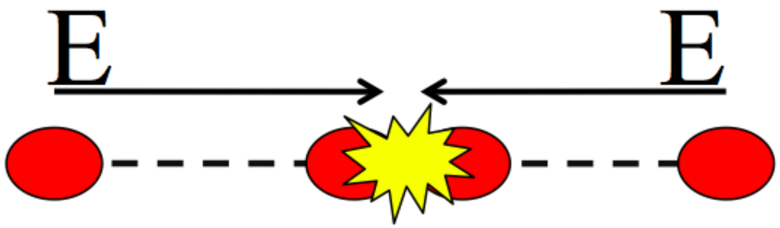
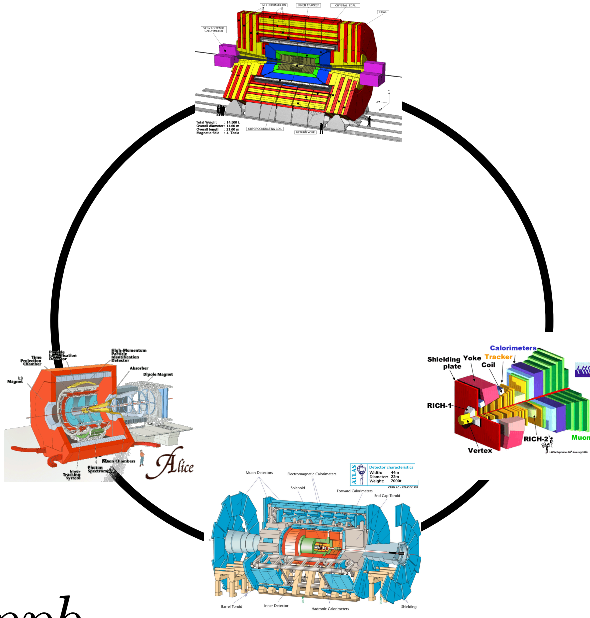


$$N_{event/s} = L \cdot \sigma_{event}$$

$$L \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b \cdot f_{rev}$$



Bunch intensity: $N_p = 1.15 - 1.65 \cdot 10^{11}\ ppb$

Transverse Beam size: $\sigma_{x,y} = 16 - 30\ \mu m$

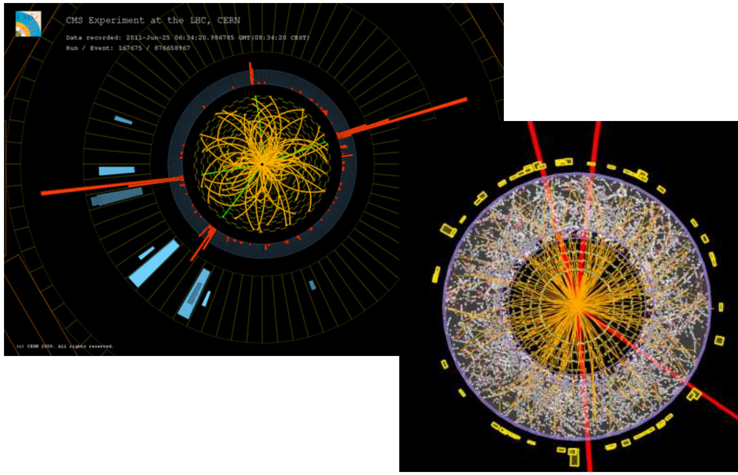
Number of bunches $1370 - 2808$

Revolution frequency $11\ kHz$

L = 10^{34} cm^{-2}s^{-1}

When do we have beam-beam effects?

- They occur when two beams get closer and Collide



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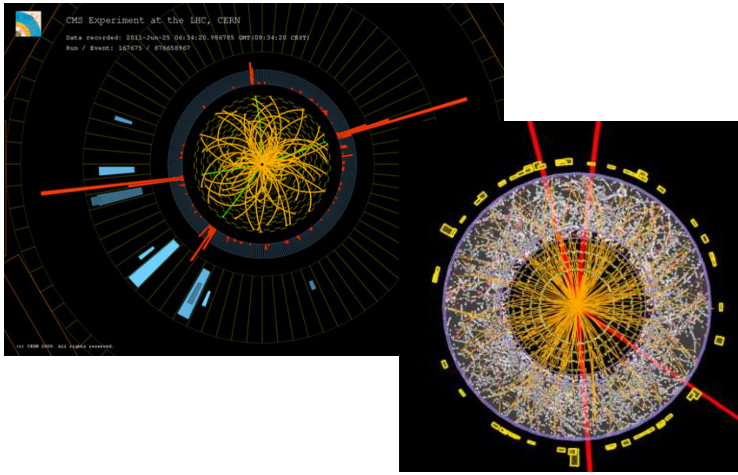
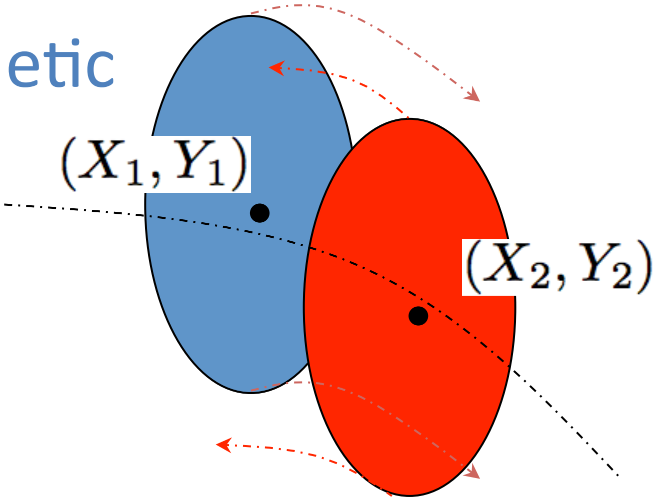
- Two types

  - High energy collisions between two particles (wanted)
  - Distortions of beam by electromagnetic forces (unwanted)





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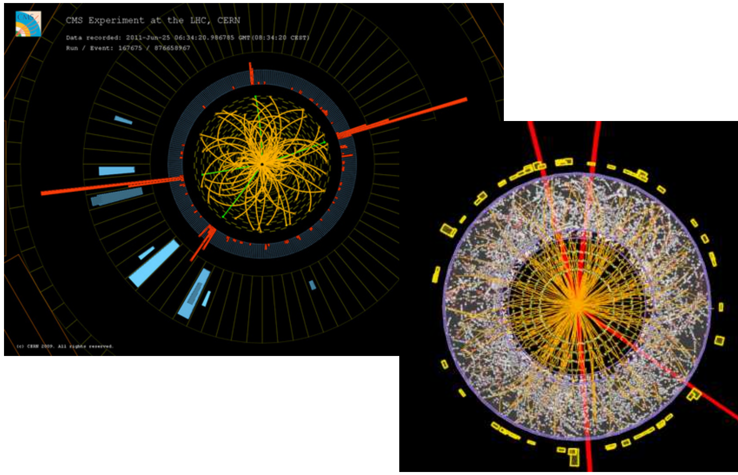

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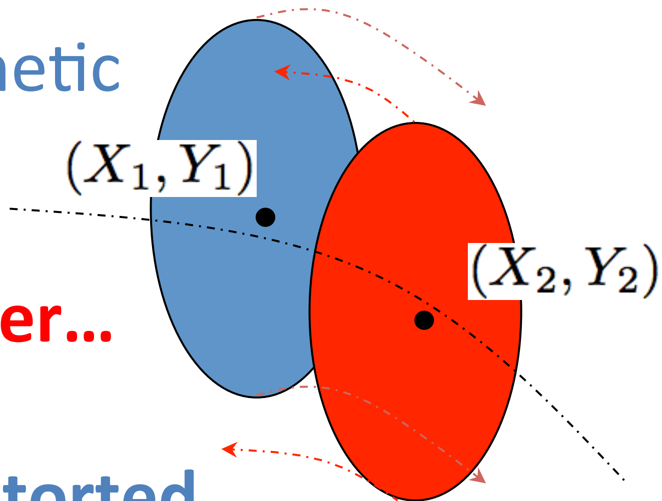

- **Unfortunately: usually both go together…**
- **0.001% (or less) of particles collide**
- **99.999% (or more) of particles are distorted**

Beam-beam effects: overview

- **Circular Colliders:** interaction occurs at every turn and beams have to be preserved for hours (10-14 hours)
  - Many effects and problems
  - Try to understand some of them
  - Several Observations

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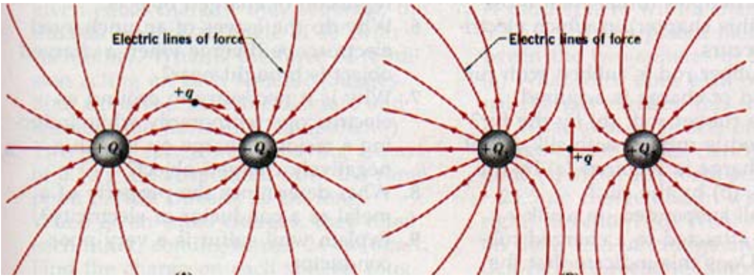
- Overview of selected effects (single particle and multi-particle effects)
- Qualitative and physical picture of the effects
- Observations from colliders
- Mathematical derivations and more info in References [1,3,4] or at

Beam-beam webpage **http://lhc-beam-beam.web.cern.ch/lhc-beam-beam/**

And CAS Proceedings

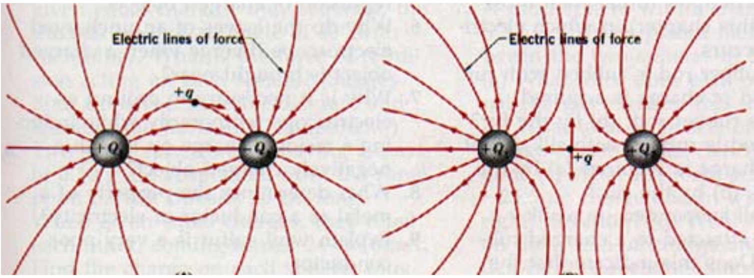
Beams EM potential

- Beam is a collection of charges



Beams EM potential

- Beam is a collection of charges
- Beam is an electromagnetic potential for other charges



Force on itself (space charge)
opposing beam (beam-beam effects)

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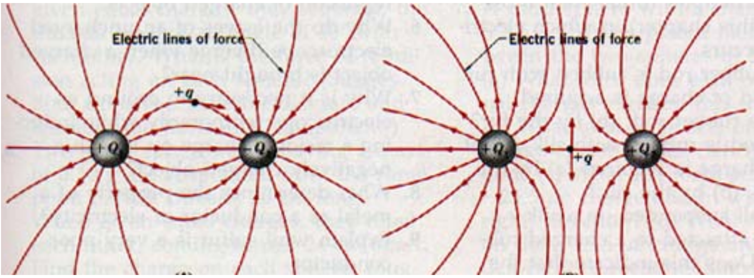

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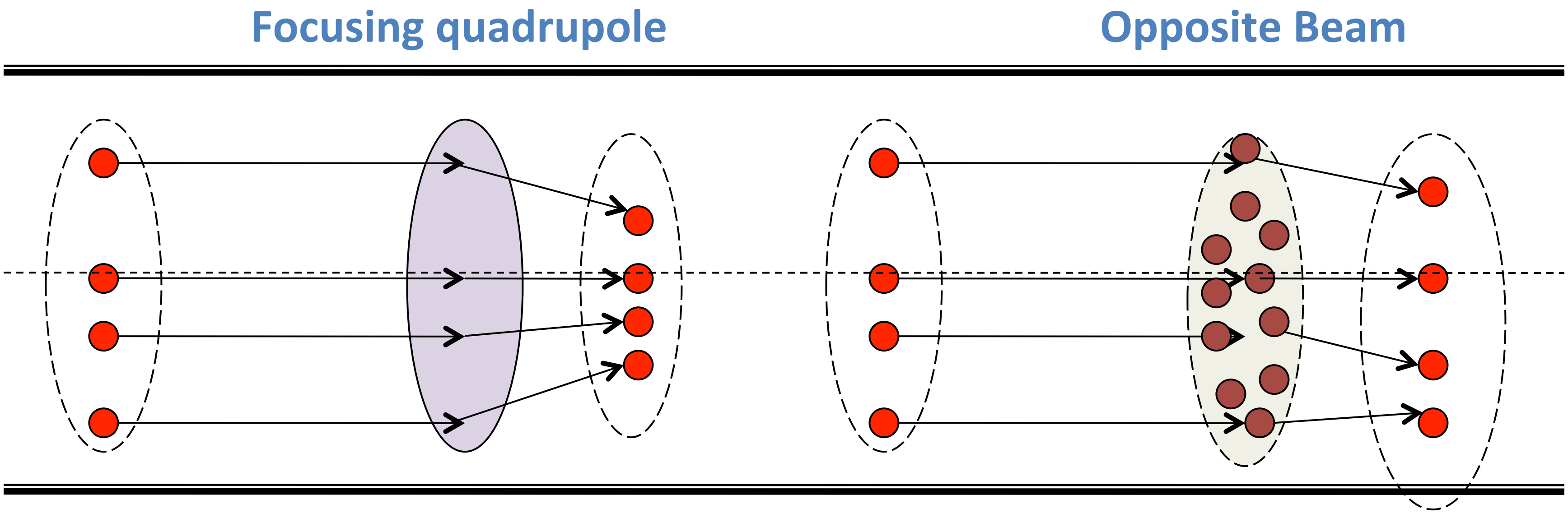
Single particle motion and whole bunch motion distorted



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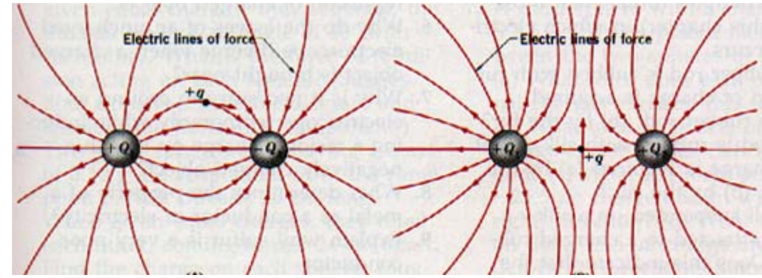

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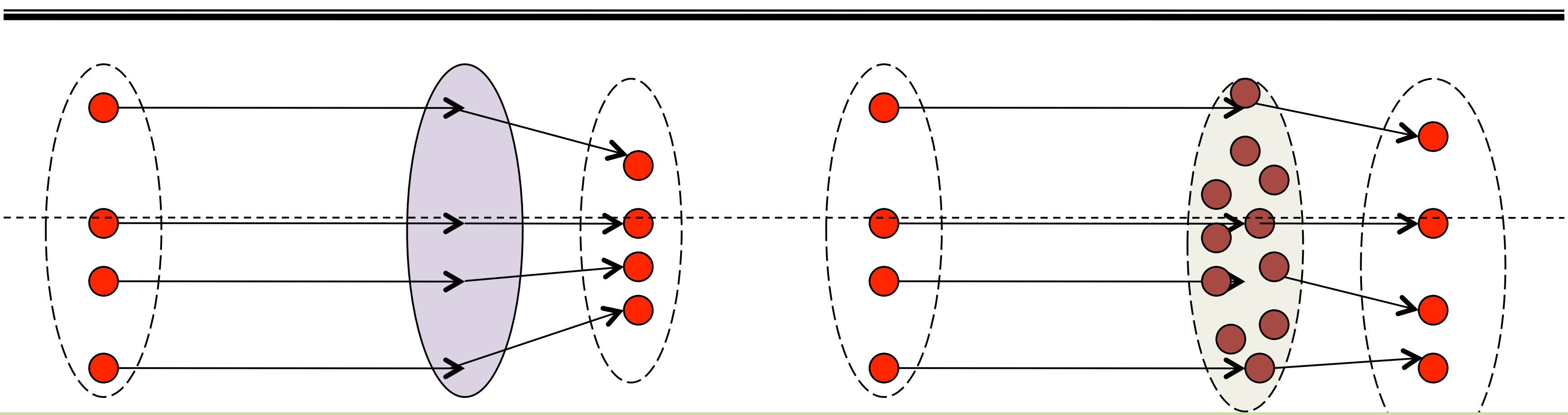
Focusing quadrupole

Opposite Beam



A beam acts on particles like an electromagnetic lens, but…

Beam-Beam Mathematics

General approach in electromagnetic problems **Reference[5]** already applied to beam-beam interactions in **Reference[1,3, 4]**

$$\Delta U = -\frac{1}{\epsilon_0}\rho(x,y,z)$$

Derive potential from Poisson equation for charges with distribution ρ

Solution of Poisson equation

$$U(x,y,z,\sigma_x,\sigma_y,\sigma_z) = \frac{1}{4\pi\epsilon_0}\int\int\int \frac{\rho(x_0,y_0,z_0)dx_0dy_0dz_0}{\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2)}}$$

$$\overrightarrow{E} = -\nabla U(x,y,z,\sigma_x,\sigma_y,\sigma_z)$$

Then compute the fields

$$\overrightarrow{F} = q(\overrightarrow{E} + \overrightarrow{v} \times \overrightarrow{B})$$

From Lorentz force one calculates the force acting on test particle with charge q

Making some assumptions we can simplify the problem and derive analytical formula for the force…

Round Gaussian distribution:

Gaussian distribution for charges

Round beams:

$$\sigma_x = \sigma_y = \sigma$$

Very relativistic, Force has only radial component :

$$\beta \approx 1 \qquad r^2 = x^2 + y^2$$

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Beam-beam Force

$$\Delta r' = \frac{1}{mc\beta\gamma} \int F_r(r, s, t)\ dt$$

$$\Delta r' = -\frac{N_p r_0}{r} \cdot \frac{r}{r^2} [1 - e^{-\frac{r^2}{2\sigma^2}}]$$

Beam-beam kick obtained integrating the force over the collision (i.e. time of passage)

Only radial component in relativistic case

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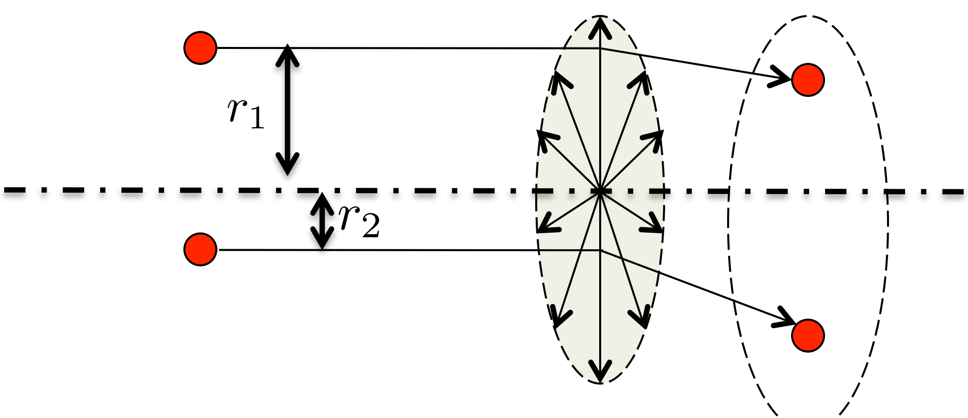

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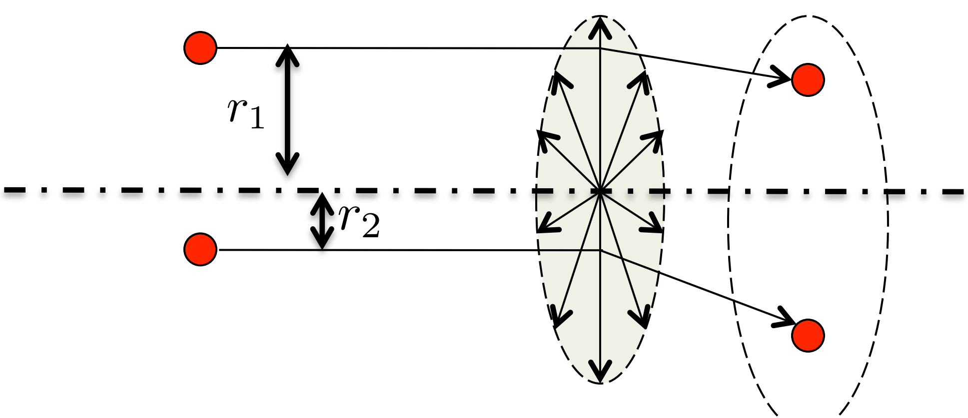
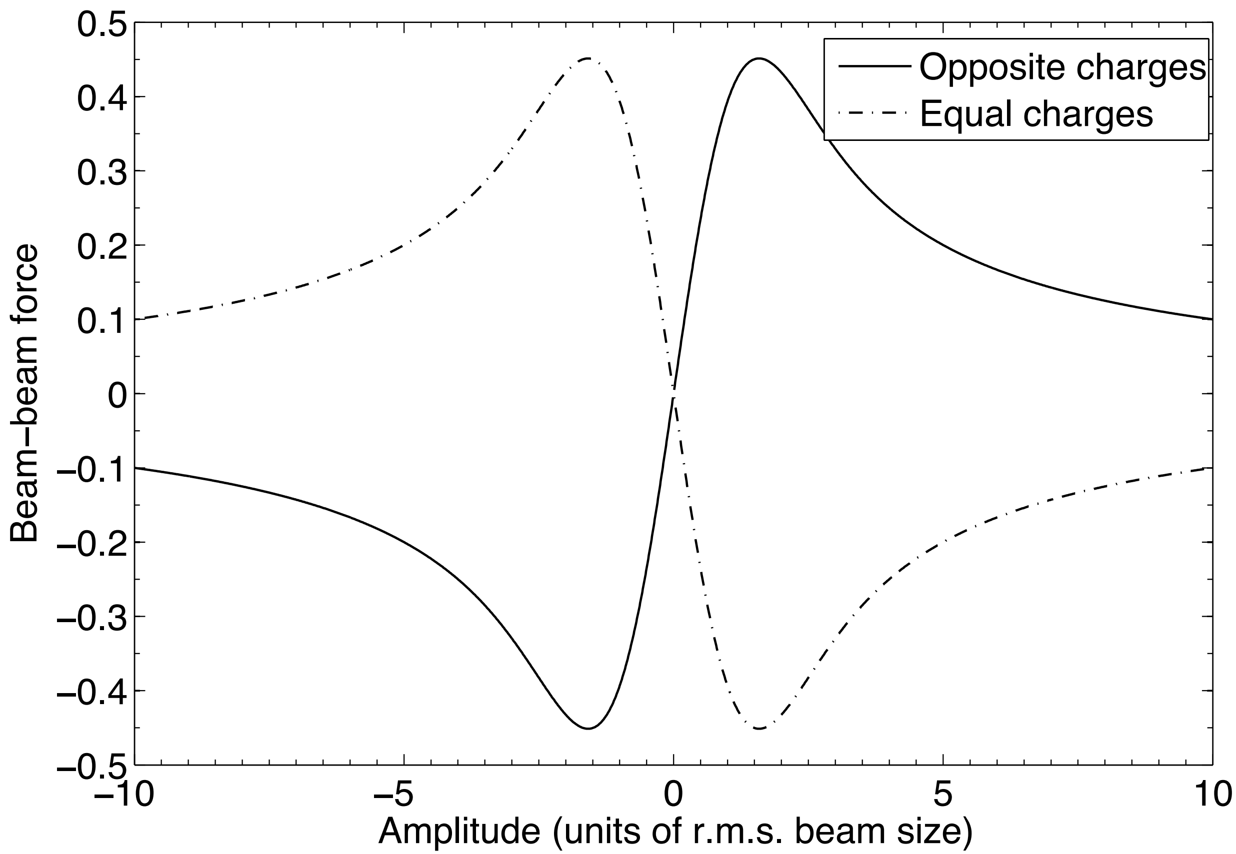


How does this force looks like?

Beam-beam Force



$$F_r(r) = \pm \frac{ne^2(1+\beta_{rel}^2)}{2\pi\epsilon_0}\frac{1}{r}[1-\exp(-\frac{r^2}{2\sigma^2})]$$

Why do we care?

Pushing for luminosity means stronger beam-beam effects

$$\mathcal{L} \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b$$

$$F \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right]$$

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Strongest non-linearity in a collider YOU CANNOT AVOID!

Physics fill lasts for many hours 10h – 24h

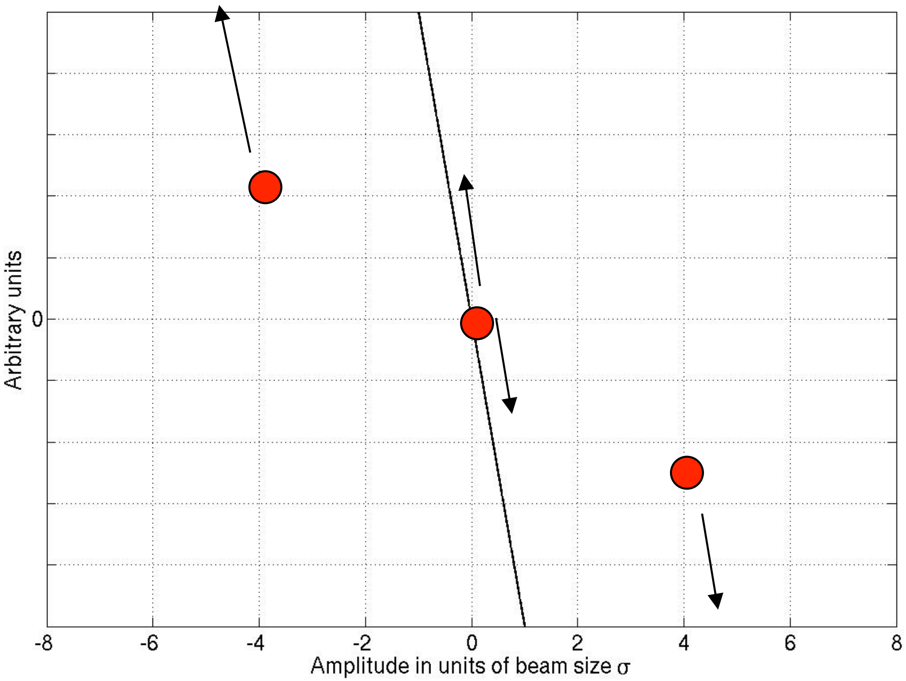
Two main questions:

What happens to a single particle?

What happens to the whole beam?

Beam-Beam Force: single particle…

Lattice defocusing quadrupole



$$F = -k \cdot r$$

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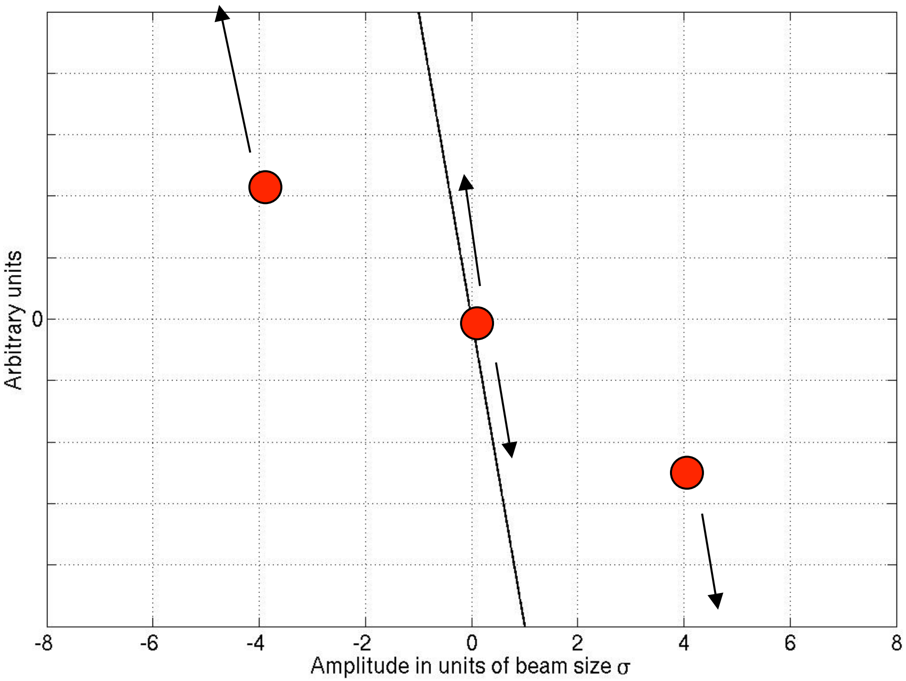

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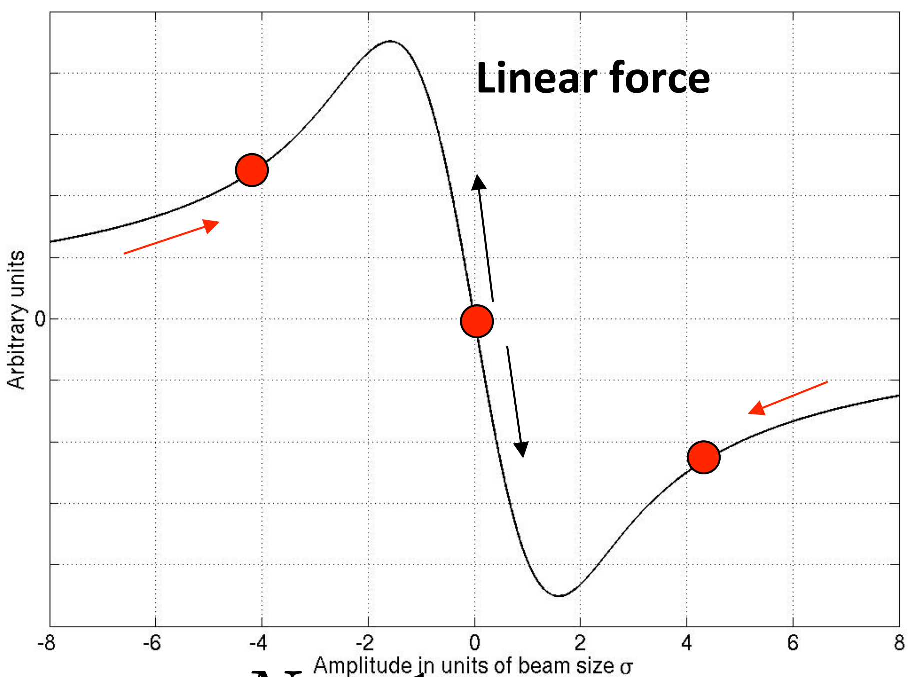

$$\mathrm{F} \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - \mathrm{e}^{-\frac{r^2}{2\sigma^2}}\right]$$

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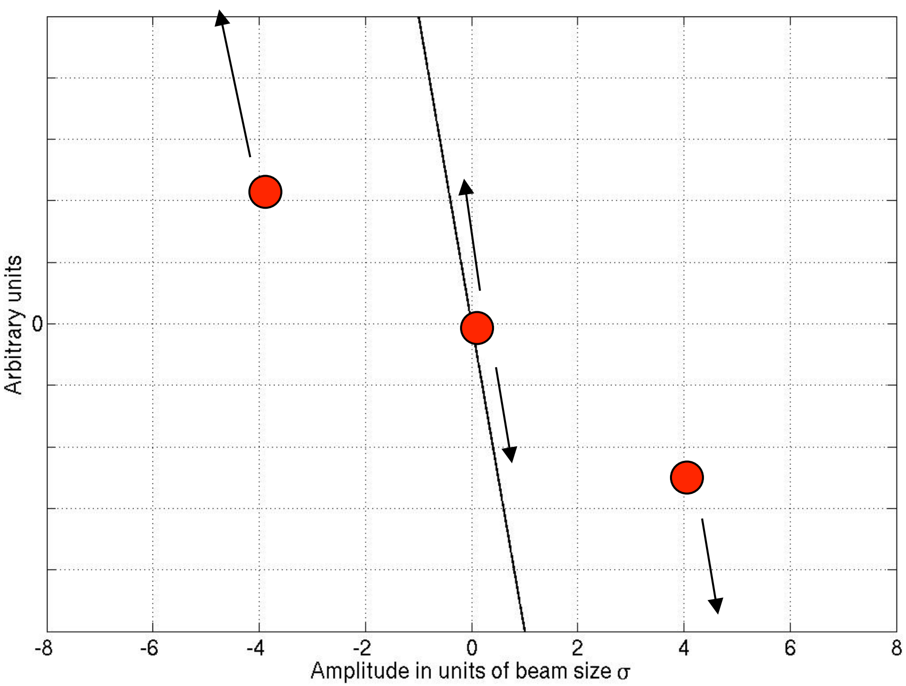

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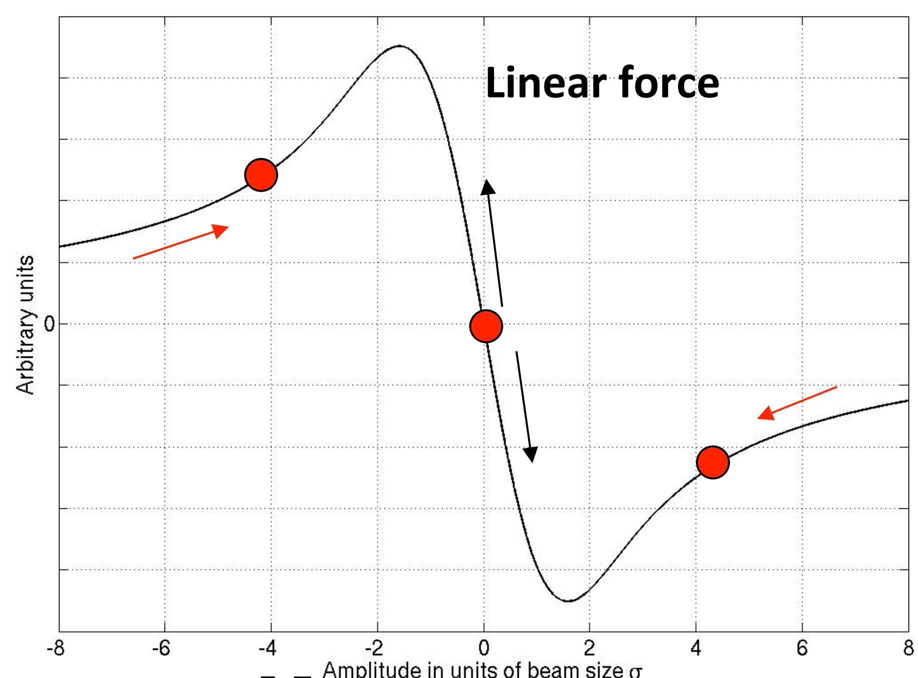


$$\mathrm{F} \propto \frac{N_p}{\sigma} \cdot \frac{1}{r} \cdot \left[1 - \mathrm{e}^{-\frac{r^2}{2\sigma^2}}\right]$$

For small amplitudes: linear force

For larger amplitudes (x > 1 σ): very non-linear!

The beam will act as a strong non-linear electromagnetic lens!

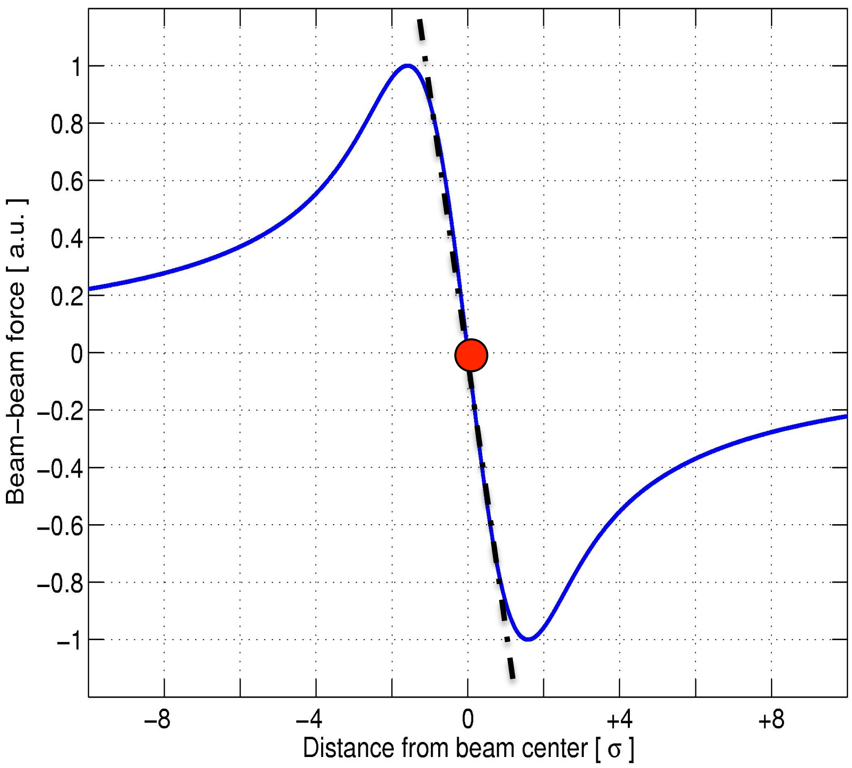
Beam-Beam parameter

Quantifies the strength of the force but does NOT reflect the nonlinear nature of the force

For small amplitudes r → 0

$$F \propto -\xi \cdot r$$

Beam-beam force



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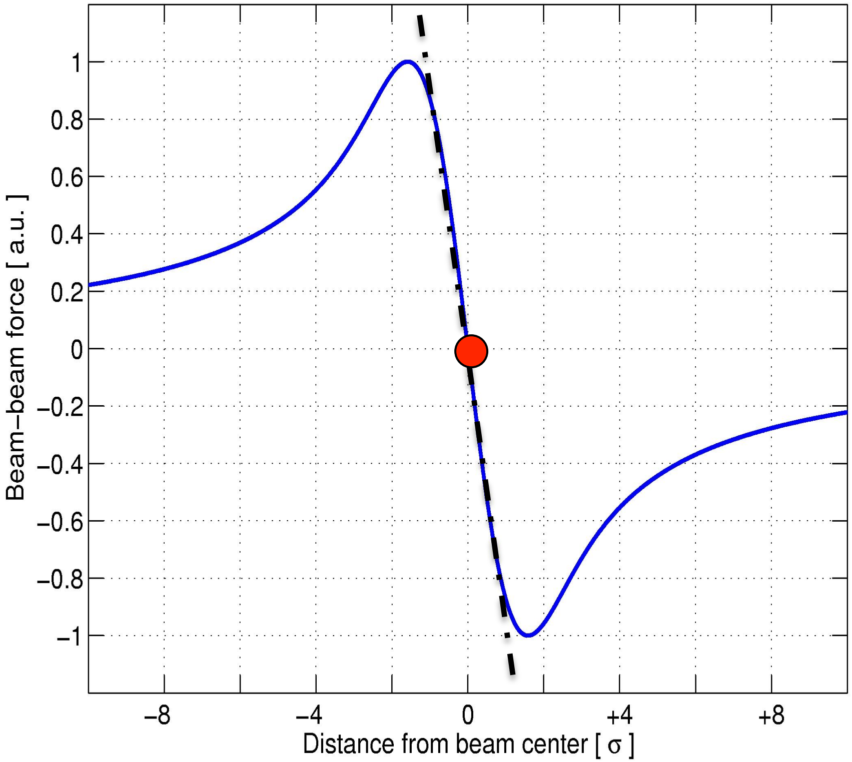

$$\Delta r' = -\frac{N_p r_0}{r} \cdot \frac{r}{r^2} \cdot \left[1 - e^{-\frac{r^2}{2\sigma^2}}\right]$$

$$\Delta r' = \frac{2N_p r_0}{\gamma} \cdot \frac{1}{r} \cdot \left[1 - \left(1 - \frac{r^2}{2\sigma^2} + \ldots\right)\right]$$

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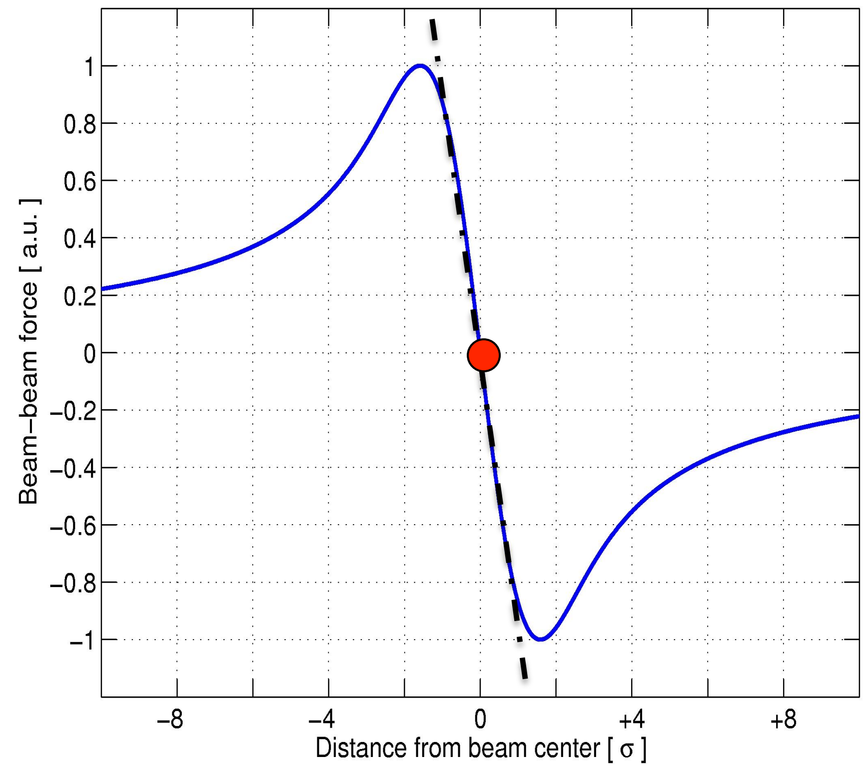
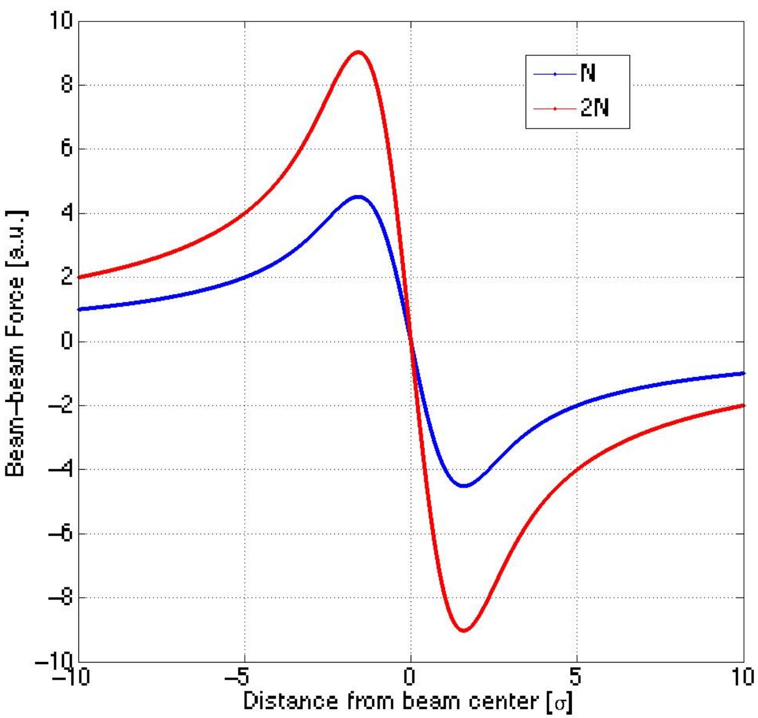
The slope of the force gives you the beam-beam parameter ξ

Beam-beam force





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Beam-Beam parameter:

For round beams:

$$\xi = \frac{\beta^*}{4\pi} \cdot \frac{\delta(\Delta r')}{\delta r} = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}$$

For non-round beams:

$$\xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

Examples:

Parameters	LEP (e^+e^-)	LHC(pp)	LHC 2015	HL-LHC
Intensity $N_{p,e}$/bunch	$4\ 10^{11}$	$1.15\ 10^{11}$	$1.7\ 10^{11}$	$2.2\ 10^{11}$
Energy GeV	100	7000	6500	7000
Beam size H	160-200 μm	16.6 μm	18 μm	10 μm
Beam size V	2-4 μm	16.6 μm	18 μm	10 μm
$\beta_{x,y}^*$ m	1.25-0.05	0.55-0.55	0.4-0.4	0.15-0.15
Crossing angle μrad	0	285	290	590
$\xi_{bb/IP}$	**0.08**	**0.0037**	**0.009**	**0.01**

B-factory maximum beam-beam parameter of 0.16

1 turn map with linearized BB

For small amplitudes beam-beam can be approximated as linear force as a quadrupole

$$F \propto -\xi \cdot r$$

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Focal length:

$$\frac{1}{f} = \frac{\Delta x'}{x} = \frac{N r_0}{\gamma \sigma^2} = \frac{\xi \cdot 4\pi}{\beta^*}$$

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Beam-beam matrix:

$$\begin{pmatrix} 1 & 0 \\ -\frac{\xi \cdot 4\pi}{\beta^*} & 1 \end{pmatrix}$$

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Perturbed one turn matrix with perturbed tune ΔQ and beta function at the IP β*:

$$\begin{pmatrix} cos(2\pi(Q+\Delta Q)) & \beta^* sin(2\pi(Q+\Delta Q)) \\ -\frac{1}{\beta^*} sin(2\pi(Q+\Delta Q)) & cos(2\pi(Q+\Delta Q)) \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix} \cdot \begin{pmatrix} cos(2\pi Q) & \beta_0^* sin(2\pi Q) \\ -\frac{1}{\beta_0^*} sin(2\pi Q) & cos(2\pi Q) \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -\frac{1}{2f} & 1 \end{pmatrix}$$

Linear tune shift and beta beating

Solving the one turn matrix one can derive the tune shift ΔQ and the perturbed beta function at the IP β^*:

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Tune is changed

$$cos(2\pi(Q + \Delta Q)) = cos(2\pi Q) - \frac{\beta_0^* \cdot 4\pi\xi}{\beta^*} sin(2\pi Q)$$

β-function is changed:

$$\frac{\beta^*}{\beta_0^*} = \frac{sin(2\pi Q)}{sin(2\pi(Q + \Delta Q))}$$

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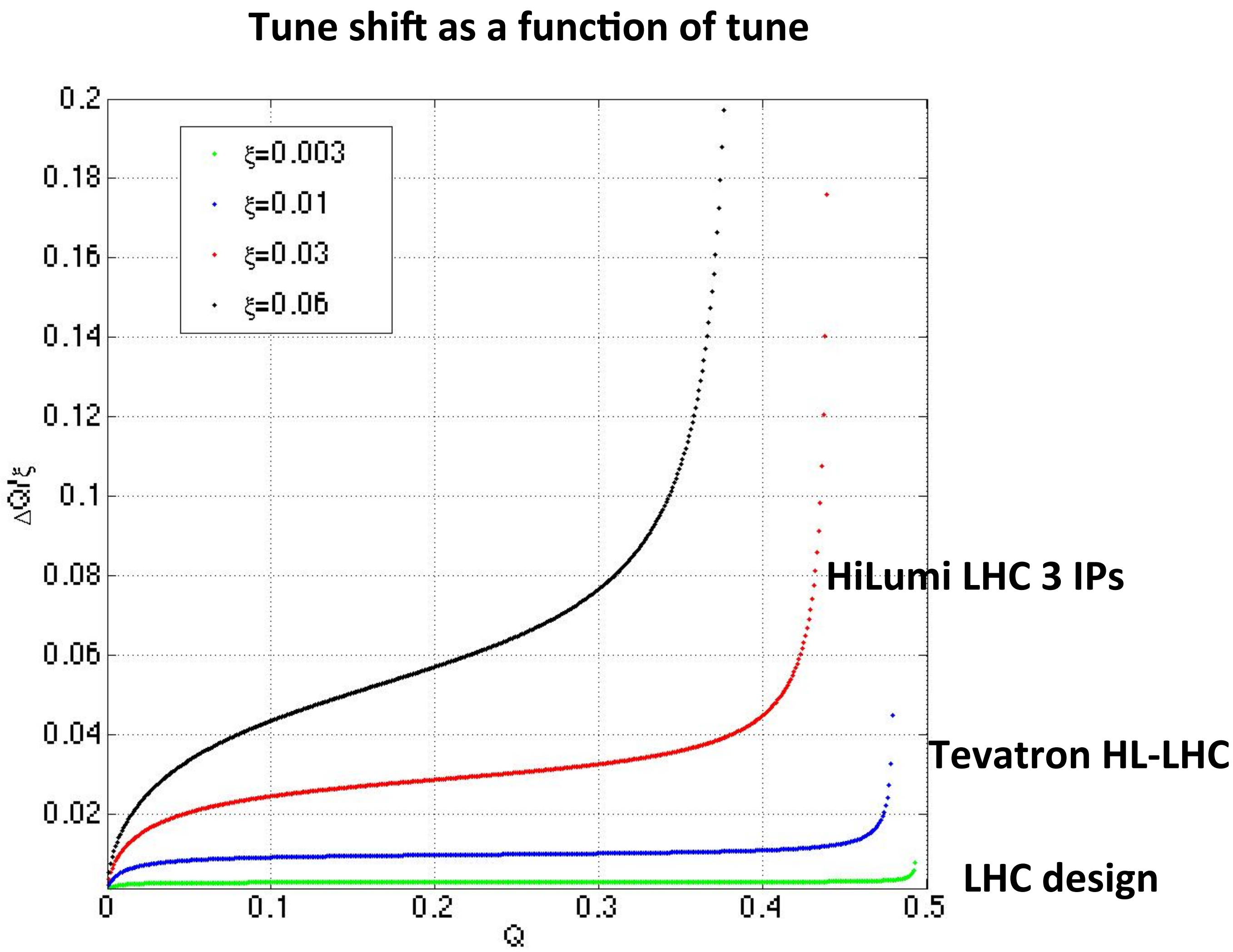
…how do they change?

Tune dependence of tune shift and dynamic beta



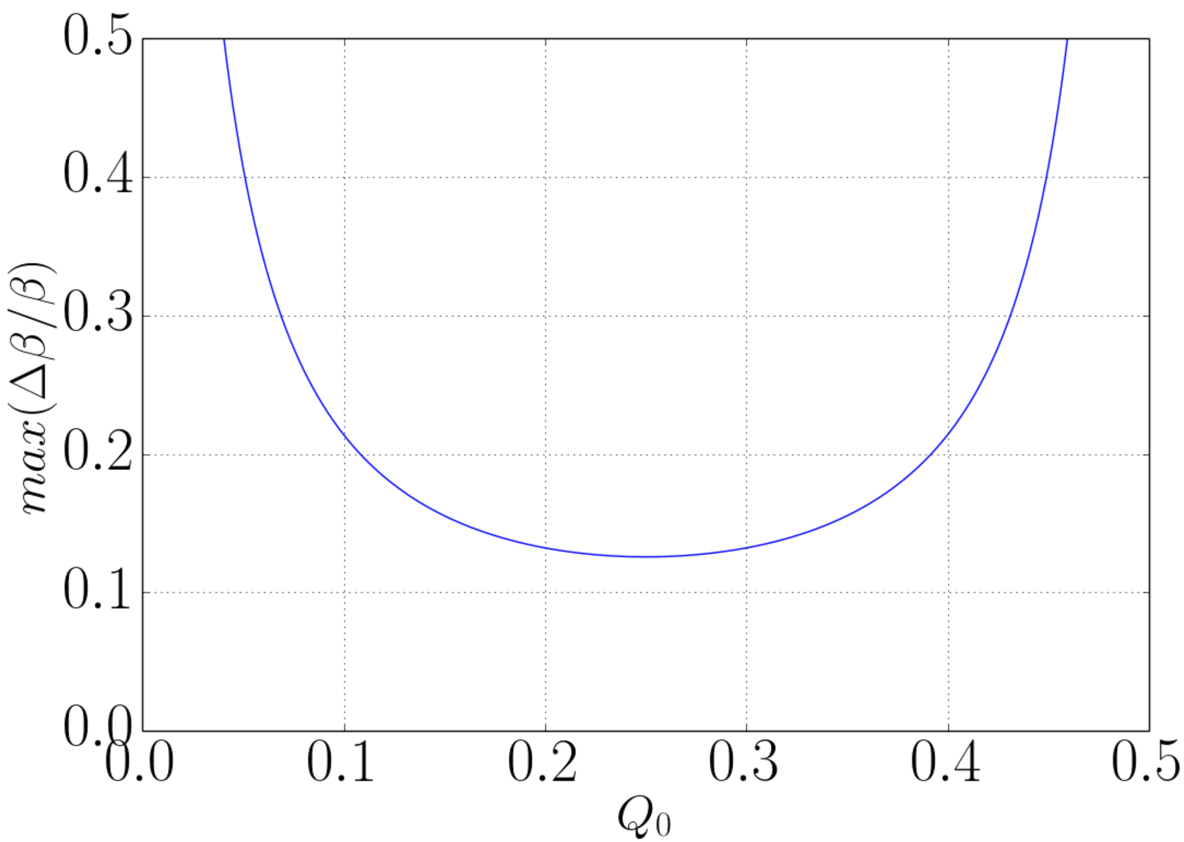
Larger ξ → Strongest variation with Q

Dynamic beta-beating due to beam-beam effects

Maximum beta change as a function of unperturbed tune

$$\max\left(\frac{\Delta\beta}{\beta}\right) = \frac{2\pi\xi}{sin(2\pi Q_0)}$$

$$\xi_{bb} = 0.02$$



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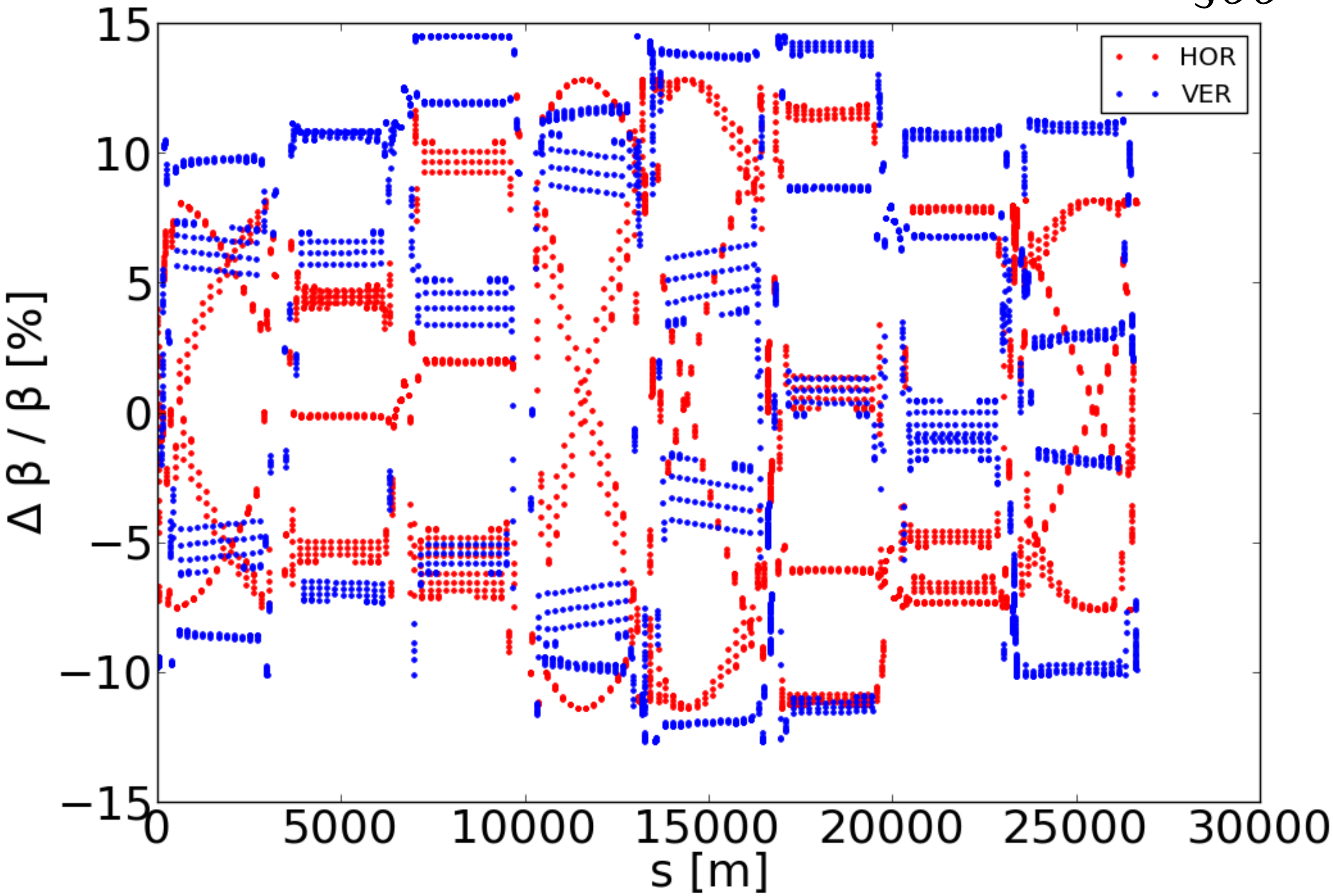
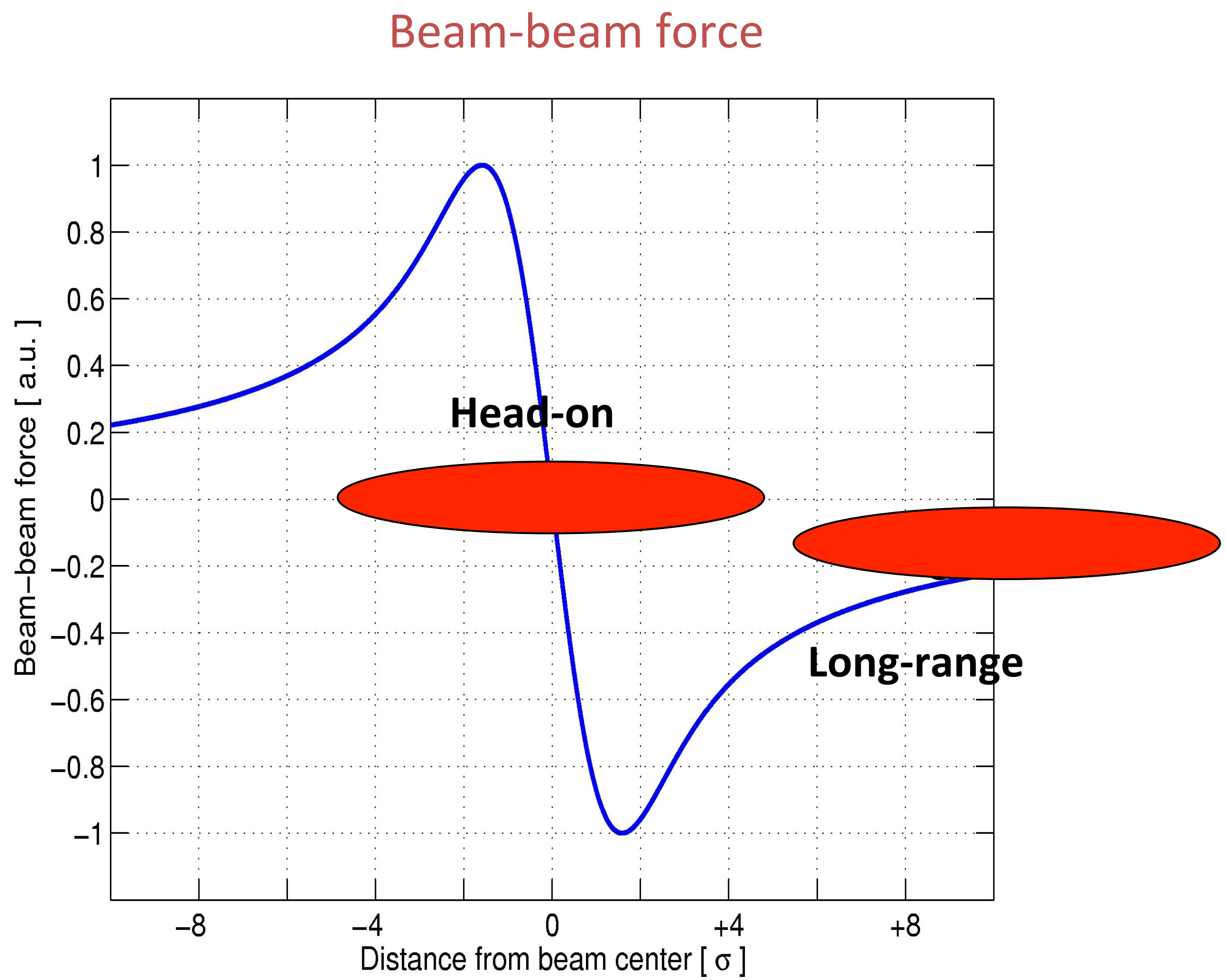


From optics codes beating along the accelerator

Head-on and Long-range interactions



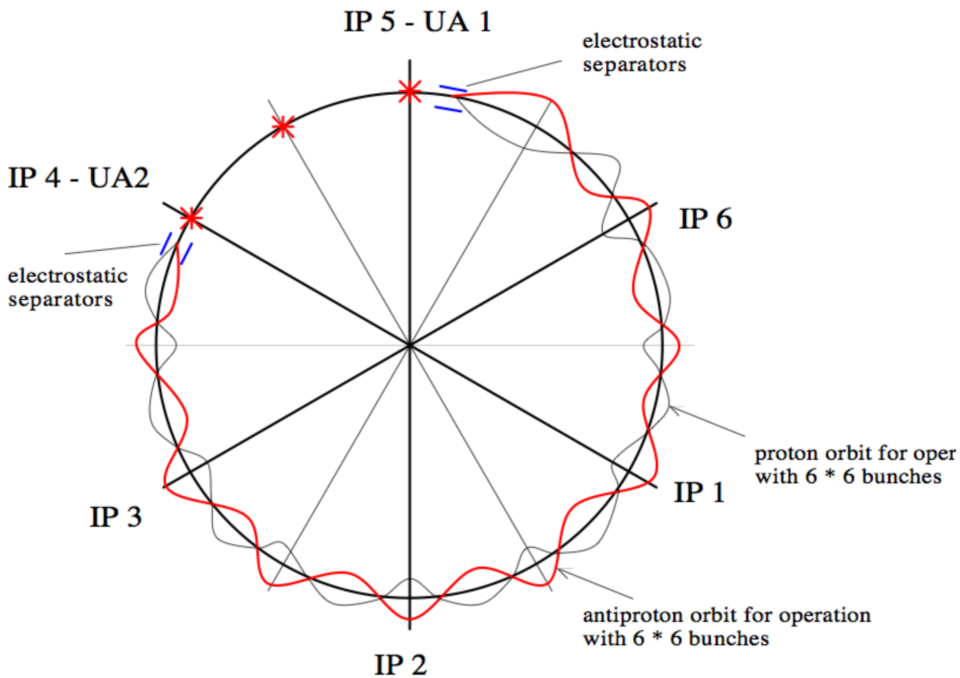
Other beam passing in the center force: HEAD-ON beam-beam interaction

Other beam passing at an offset of the force: LONG-RANGE beam-beam interaction

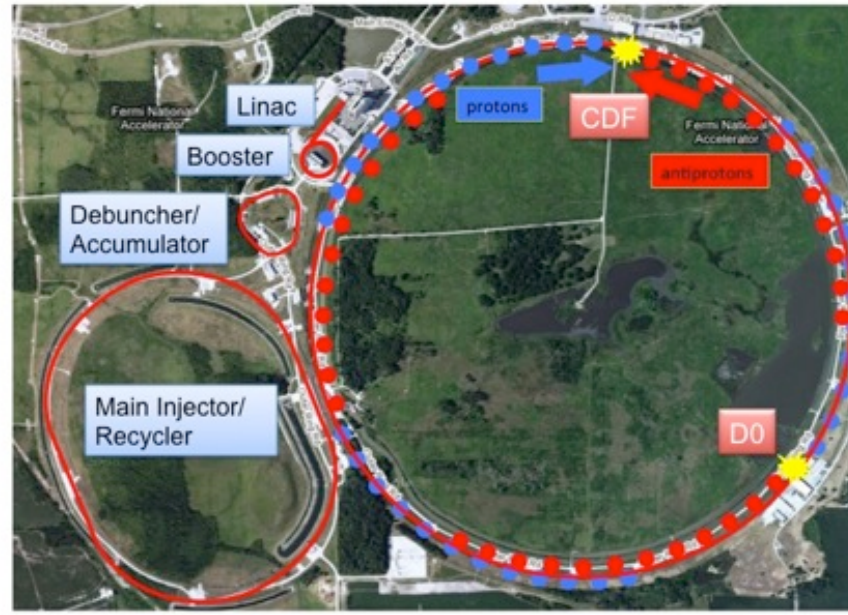
Circular colliders HO and LR

$$L \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b \cdot f_{rev}$$

SPS collider: 6 bunches
3 HO and 9 LR

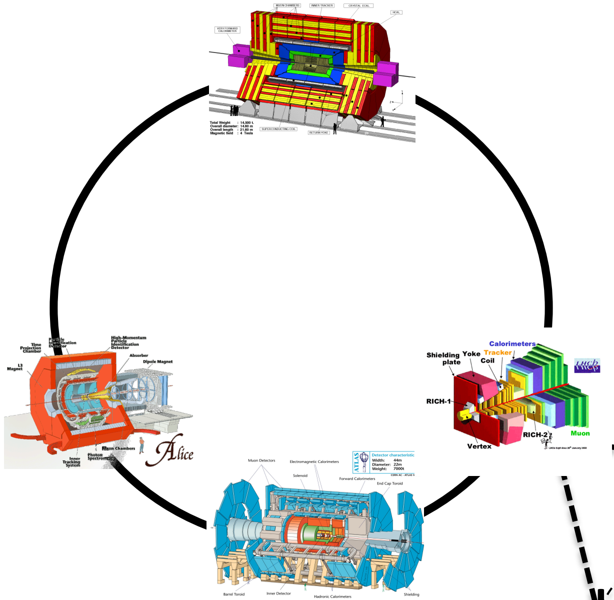


RHIC: 110 bunches
2 BBIs Head-on



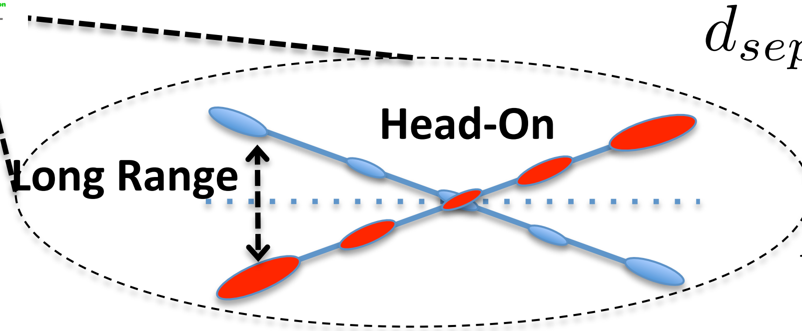
Tevatron: 36 bunches
2 BBIs Head-on and 72 Long-range

LHC, KEKB… colliders



- Crossing angle operation
- High number of bunches in train structures

$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$

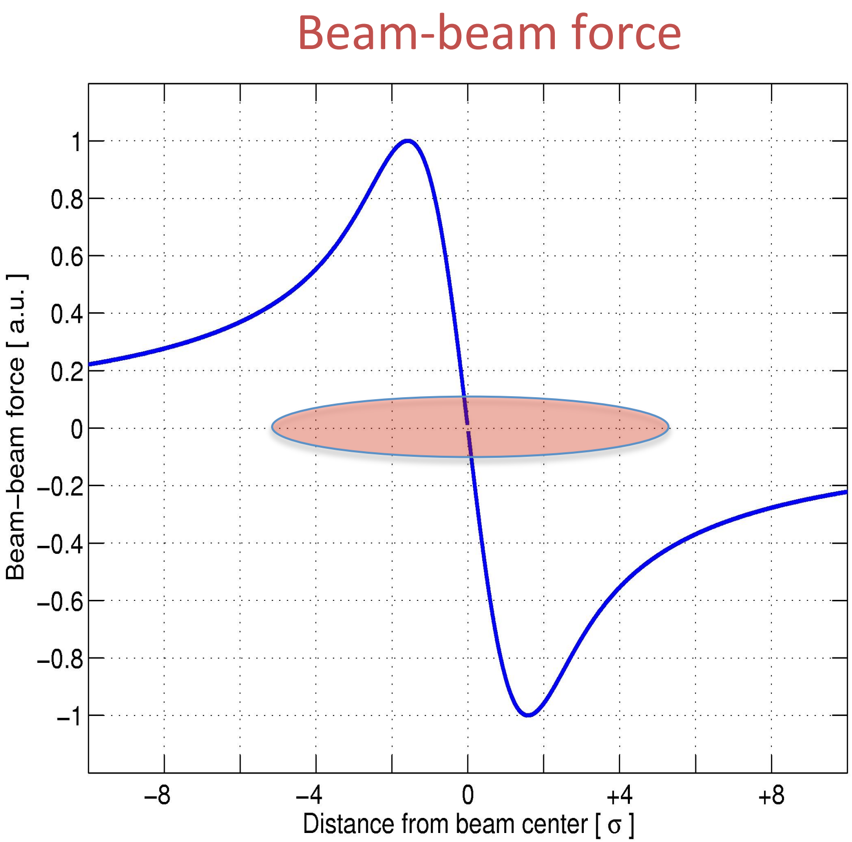


$$L = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \cdot S$$

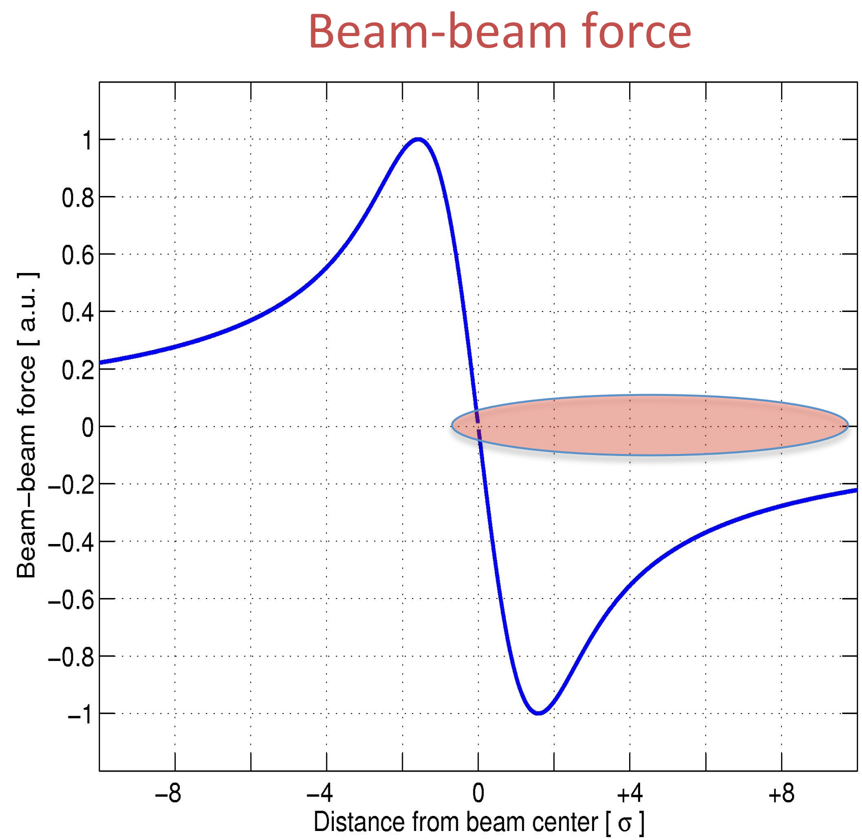
72 bunches

	SppS	Tevatron	RHIC	LHC
Number Bunches	6	36	109	2808
LR interactions	9	70	0	120/40
Head-on interactions	3	2	2	4

A beam will experience all the force range



Second beam passing in the center
HEAD-ON beam-beam interaction



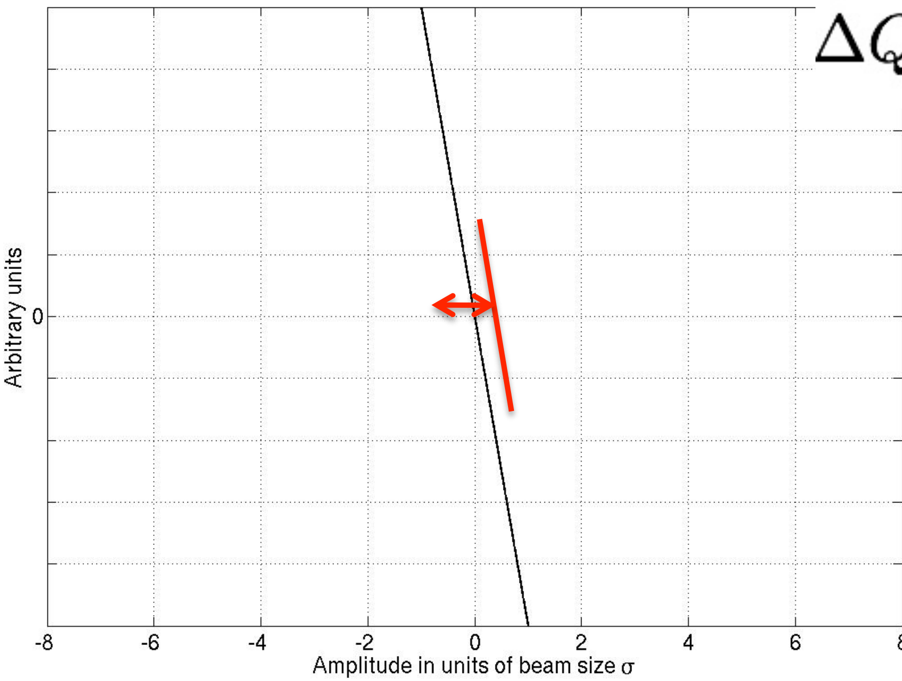
Second beam displaced offset
LONG-RANGE beam-beam interaction

Tune shift as a function of amplitude (detuning with amplitude or tune spread)

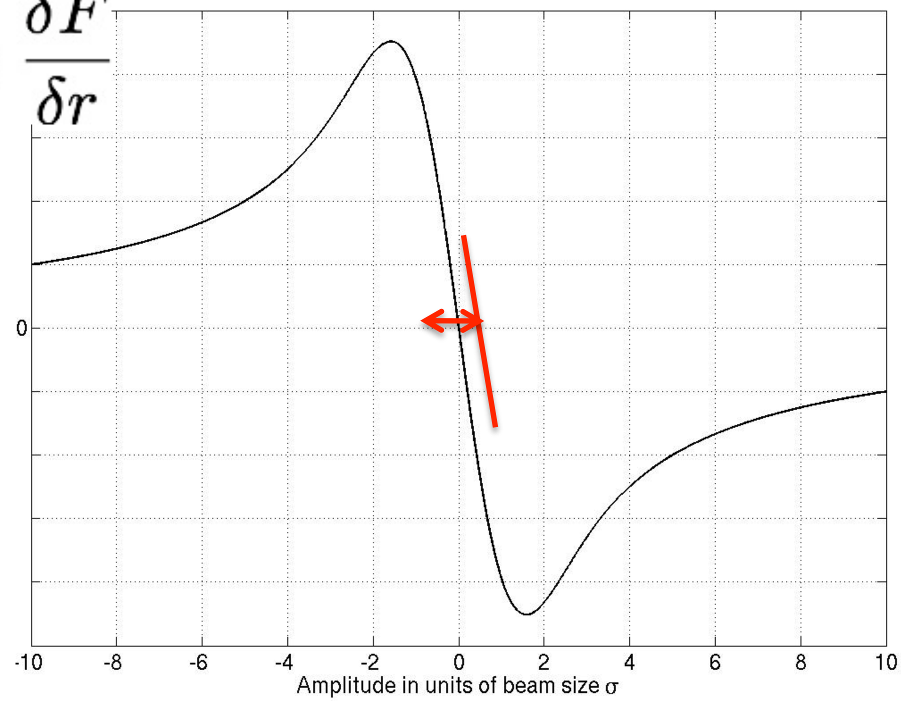
Detuning with Amplitude for head-on

Instantaneous tune shift of test particle when it crosses the other beam is related to the derivative of the force with respect to the amplitude

$$\Delta Q \propto \frac{\delta F}{\delta r}$$



$$\Delta Q_{quad} = const$$



$$\Delta Q_{bb} \approx const$$

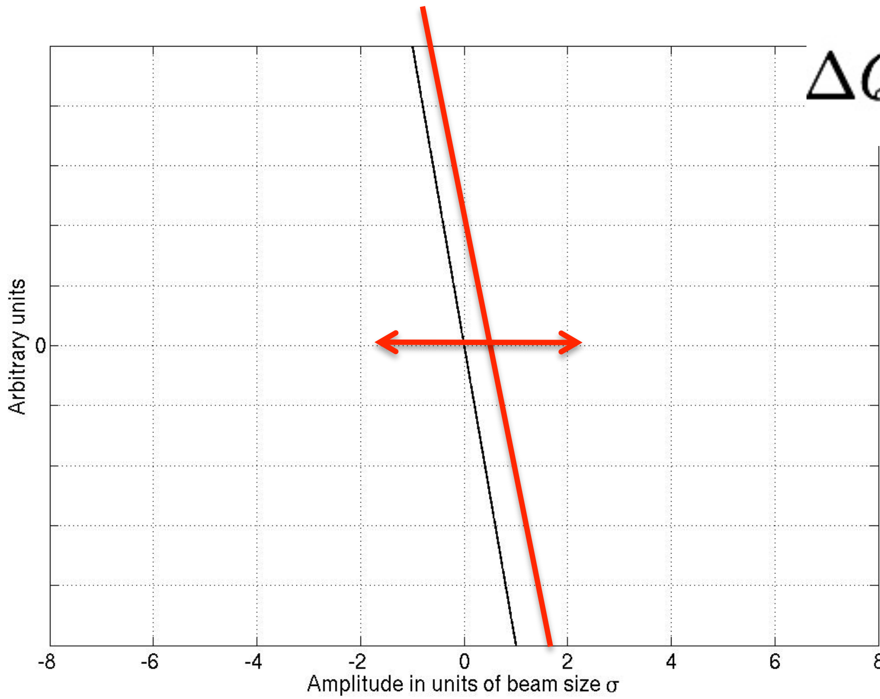
For small amplitude test particle linear tune shift

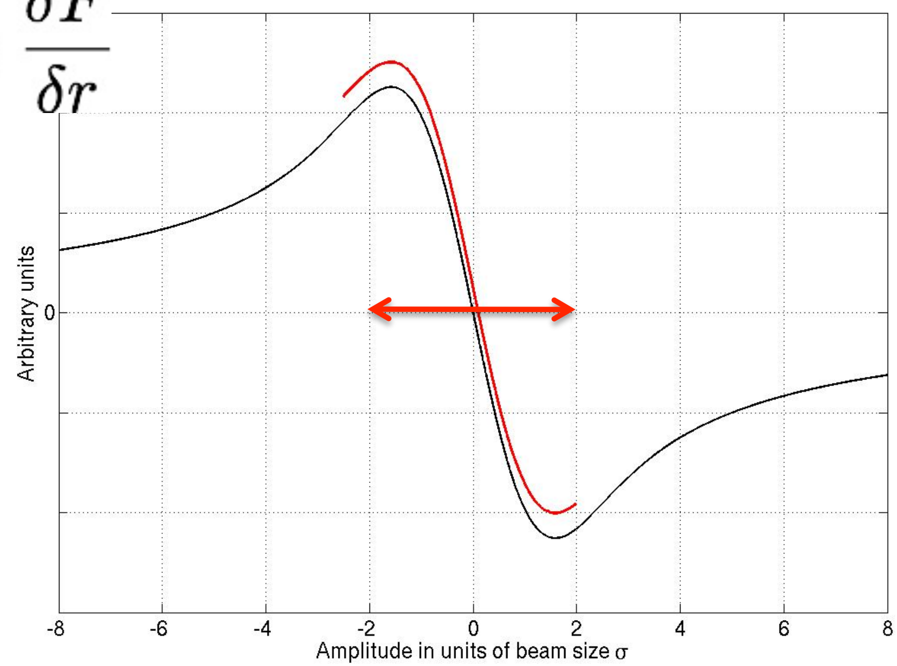
$$\lim_{r\to 0} \Delta Q(r) = -\frac{N r_0 \beta^*}{4\pi\gamma\sigma^2} = \xi$$

Detuning with Amplitude for head-on

Beam with many particles this results in a tune spread

$$\Delta Q \propto \frac{\delta F}{\delta r}$$





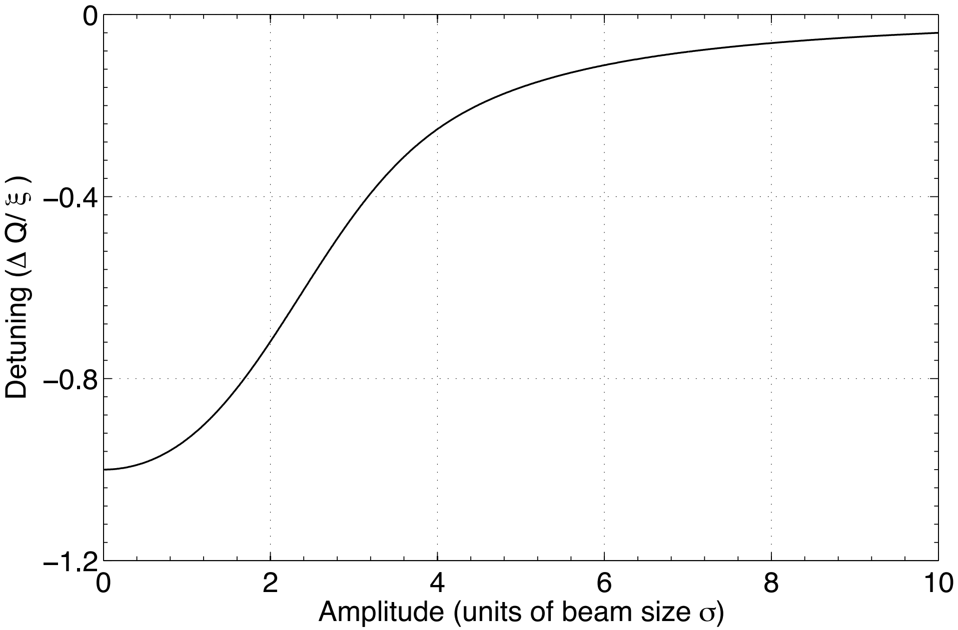
$$\Delta Q_{quad} = const \qquad \Delta Q_{bb} \neq const$$

$$\Delta Q(x) = \frac{N r_0 \beta}{4\pi\gamma\sigma^2} \cdot \frac{1}{(\frac{x}{2})^2} \cdot (\exp -(\frac{x}{2})^2 I_0(\frac{x}{2})^2 - 1)$$

Mathematical derivation in Ref [3] using Hamiltonian formalism and in Ref [4] using Lie Algebra

Head-on detuning with amplitude and footprints

1-D plot of detuning with amplitude



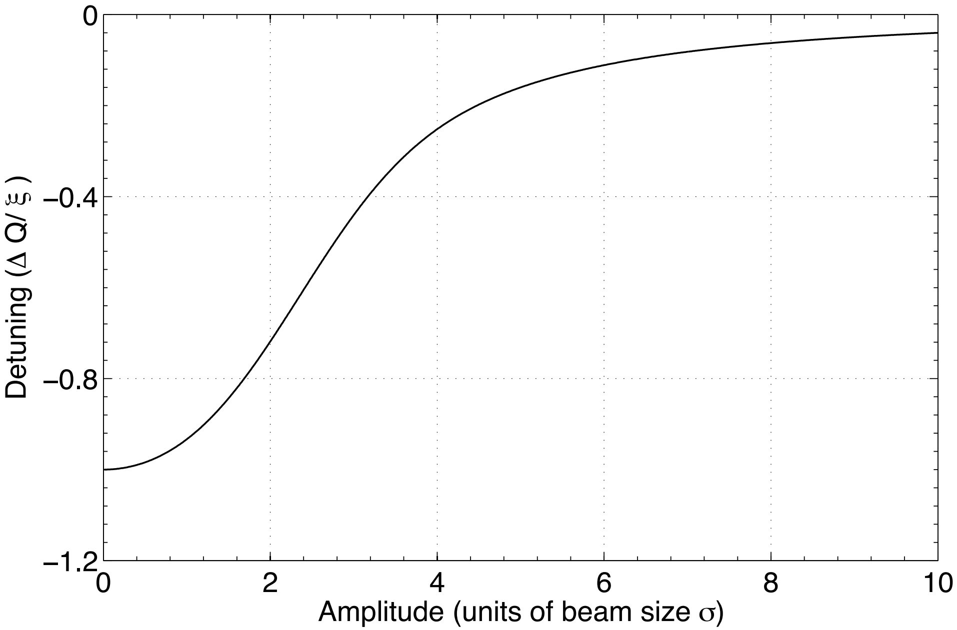
And in the other plane?

THE SAME DERIVATION

same tune spread

Head-on detuning with amplitude and footprints

1-D plot of detuning with amplitude



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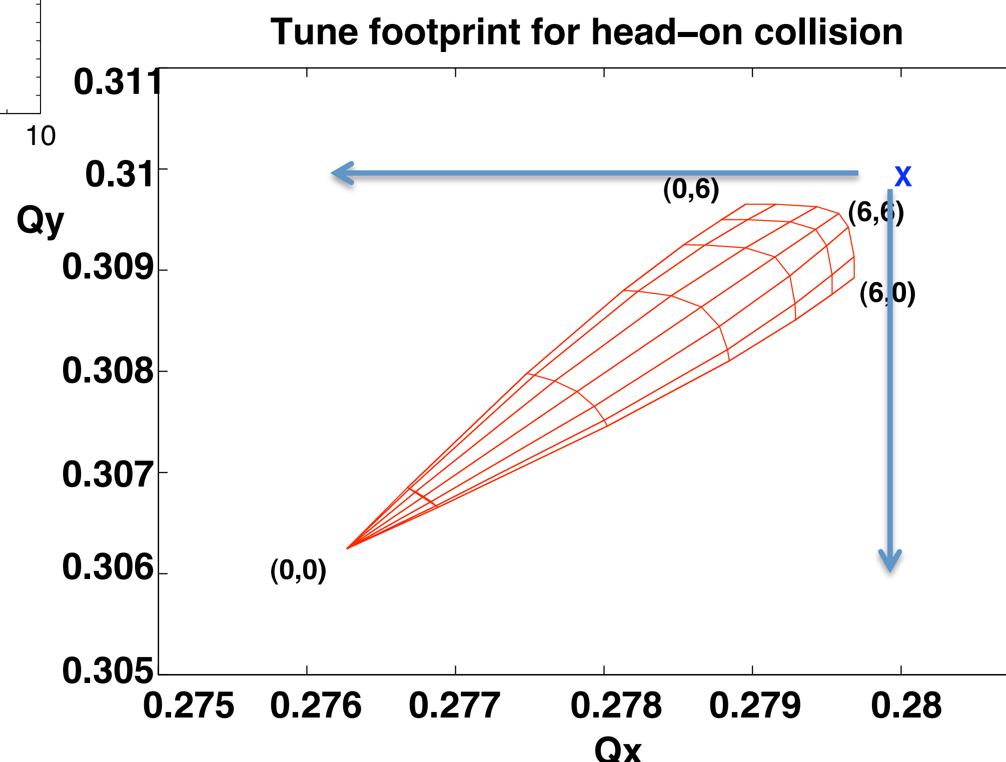
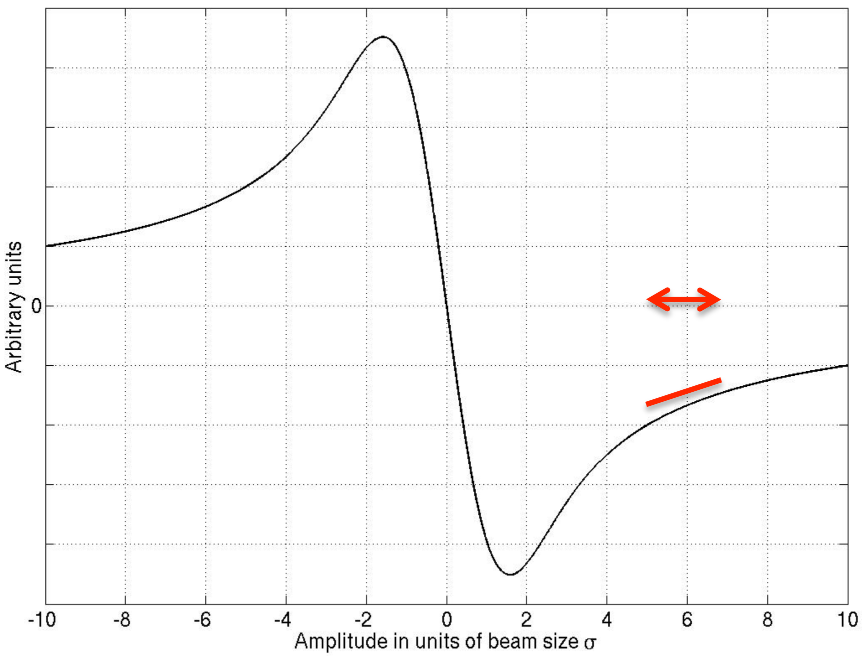


FOOTPRINT

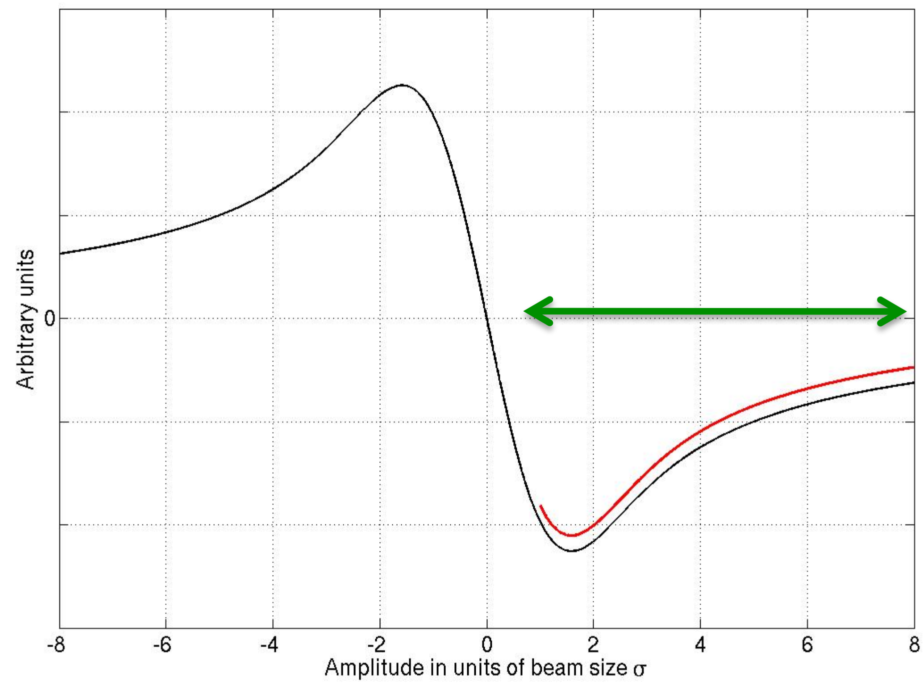
2-D mapping of the detuning with amplitude of particles

And for long-range interactions?



Second beam centered at d (i.e. 6σ)

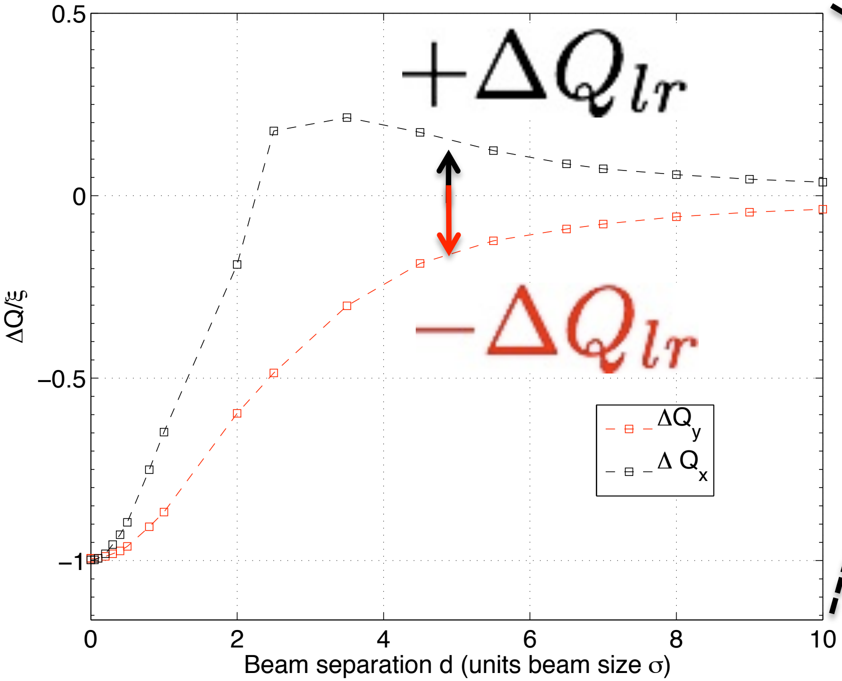
- **Small amplitude particles positive tune shifts**
- **Large amplitude can go to negative tune shifts**



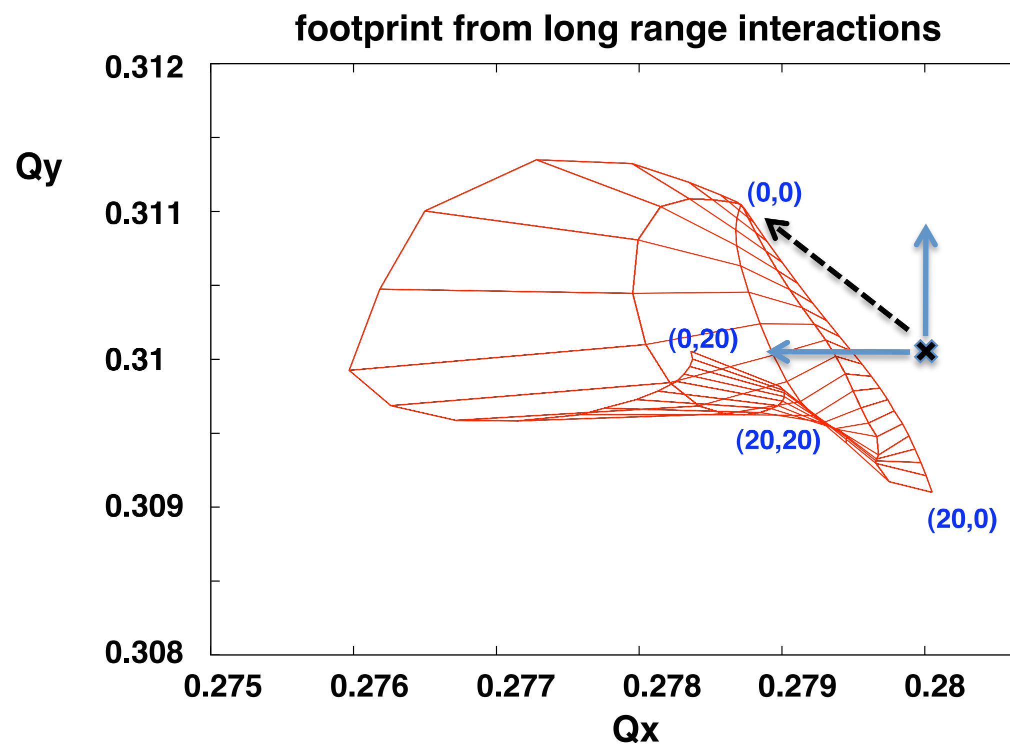
Long range tune shift scaling for distances $d > 6\sigma$

$$\Delta Q_{lr} \propto -\frac{N}{d^2}$$

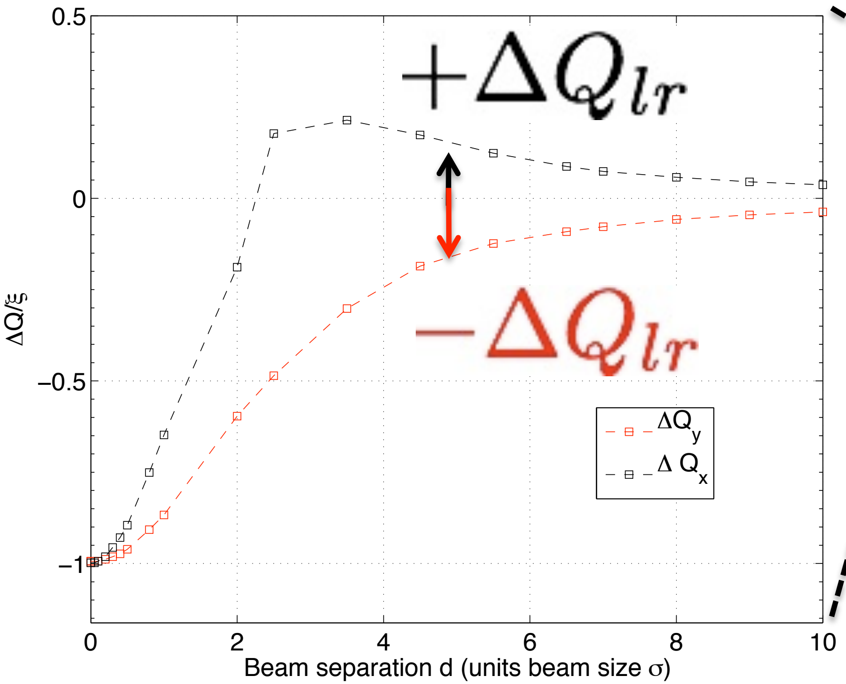
Beam-beam tune shift and spead: LRs



Tune shift as a function of separation
in horizontal plane
In the **horizontal** plane **long range tune shift**
In the **vertical plane opposite sign!**



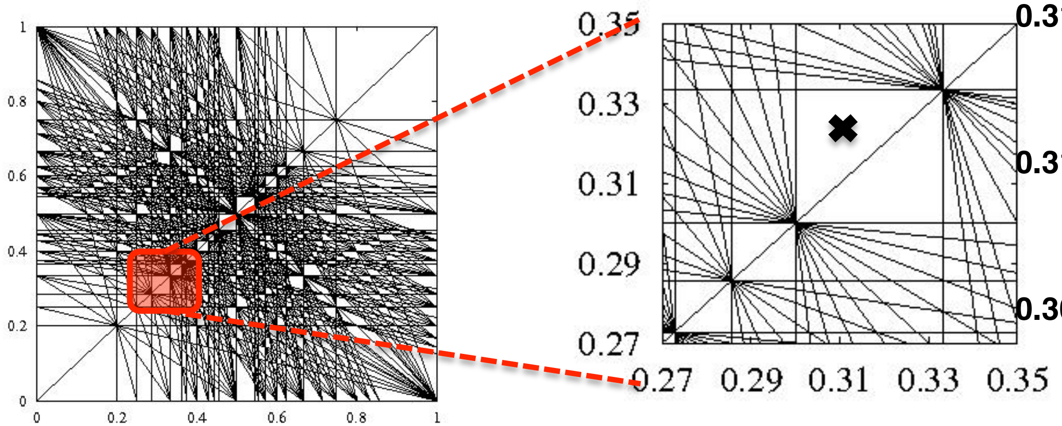
Beam-beam tune shift and spead: LRs

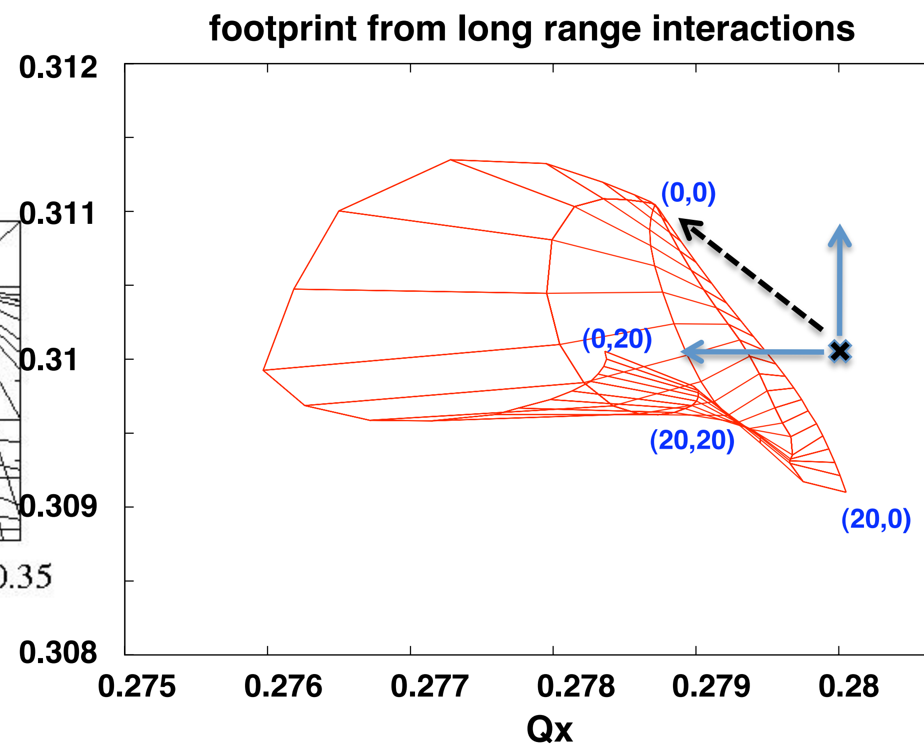


Tune shift as a function of separation in horizontal plane

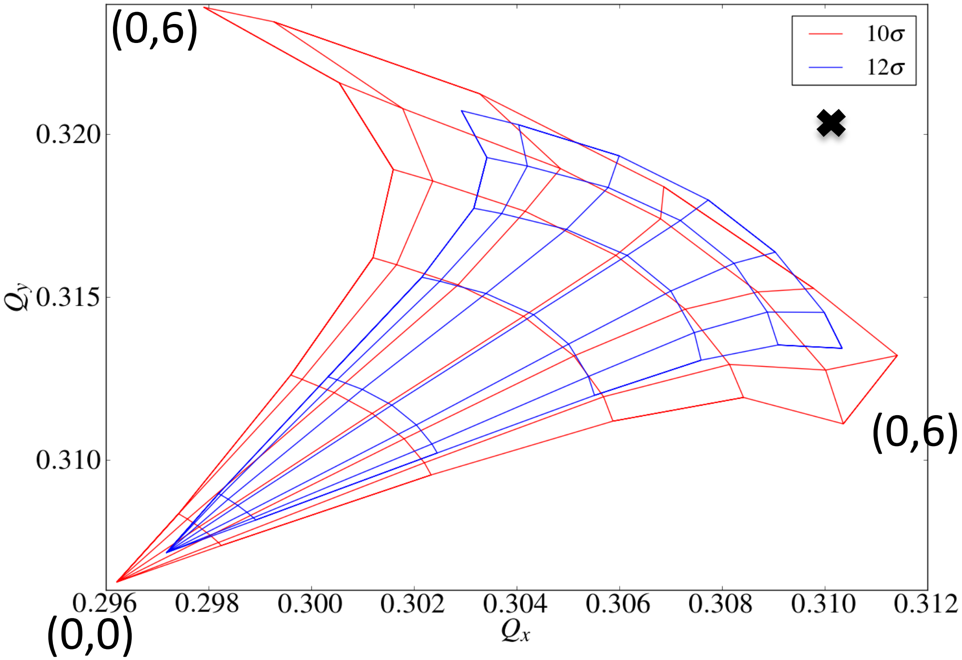
In the **horizontal** plane **long range tune shift**

In the **vertical** plane **opposite sign!**





Beam-beam tune shift and spread: HO + LRs

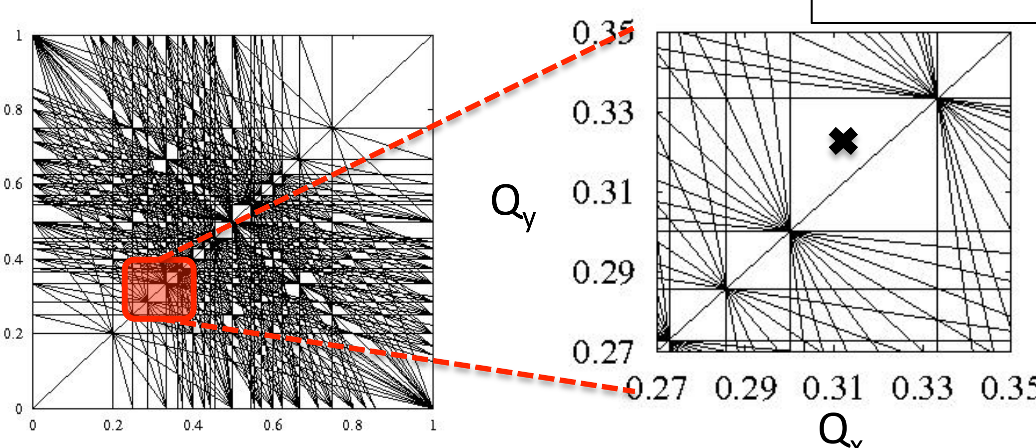


Footprints depend on:

- number of interactions (124 per turn)
- Type (Head-on and long-range)
- Separation
- Plane of interaction

Very complicated depending on collision scheme

Pushing luminosity increases this area while we need to keep it small to avoid resonances and preserve the stability of particles



Difficult to avoid resonances!

Complications

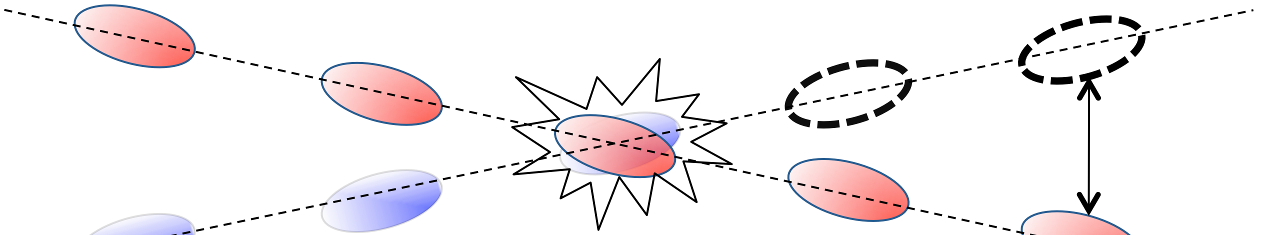
$$L \propto \frac{N_p^2}{\sigma_x \sigma_y} \cdot n_b \cdot f_{rev}$$

PACMAN and SUPER PACMAN bunches

Pacman:

miss long range BBI

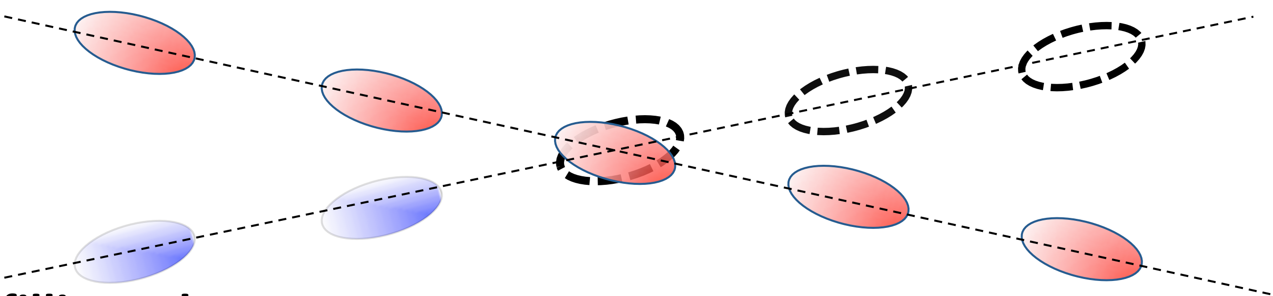
(120-40 LR interactions)



Super Pacman:

miss head-on BBI

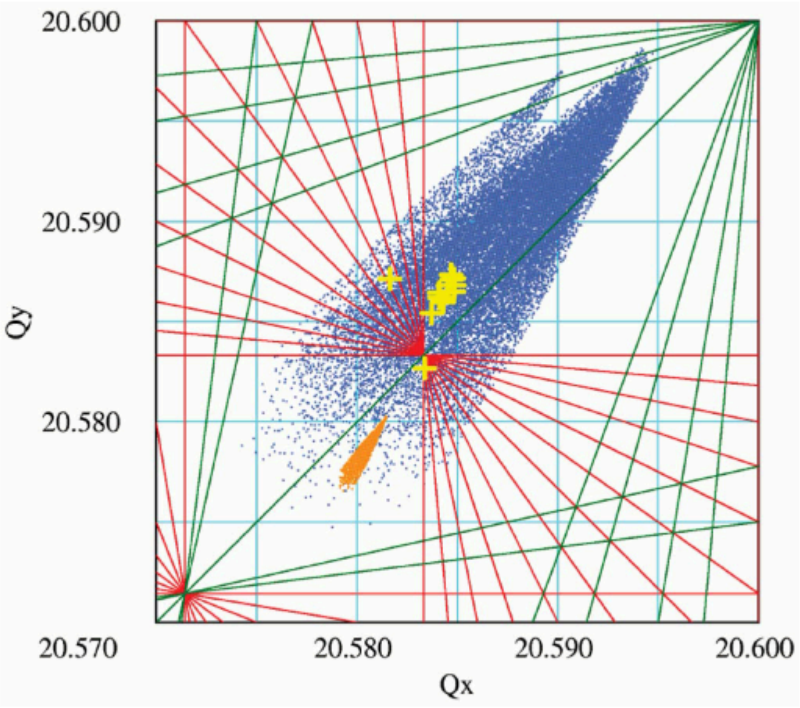
IP2 and IP8 depending on filling scheme

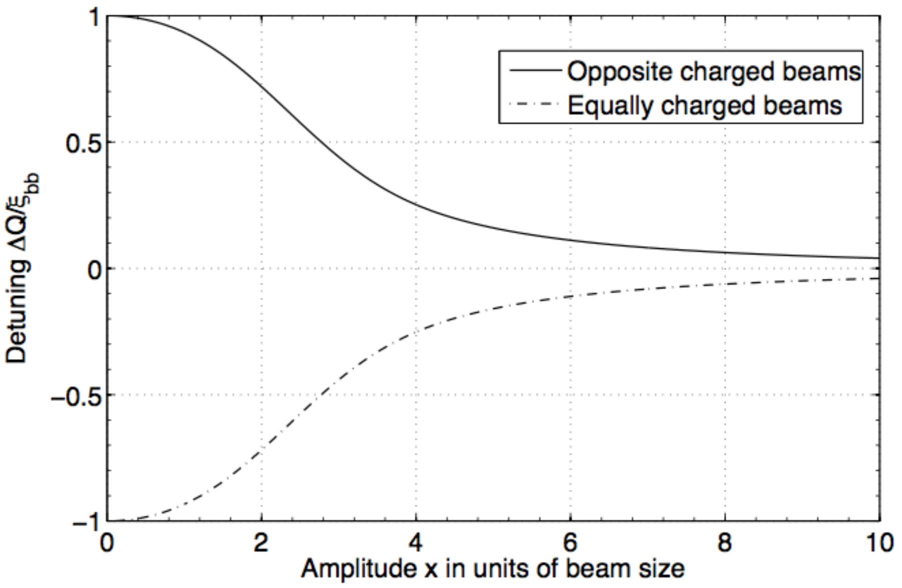


Different bunch families: Pacman and Super Pacman

Pacman and Super-pacman

Tevatron

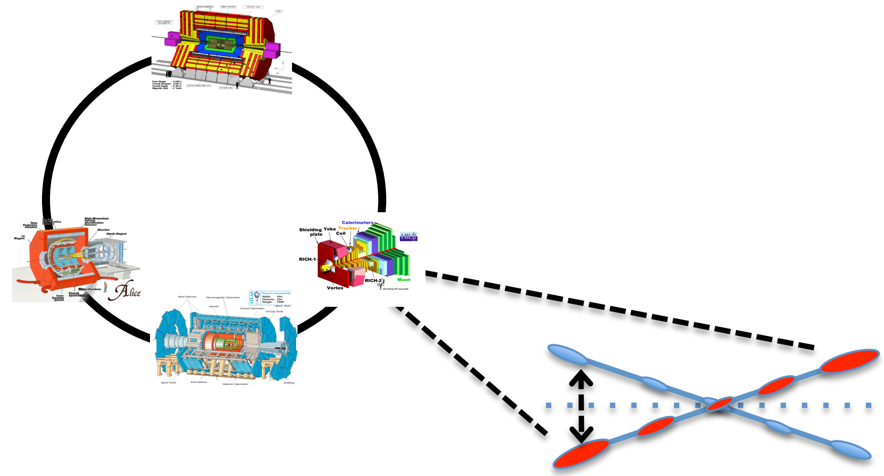




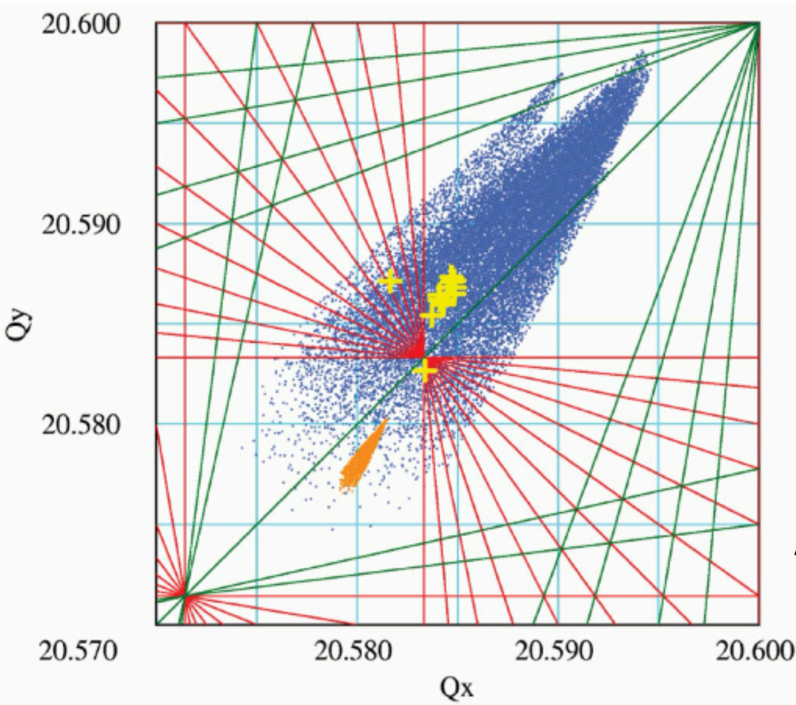
Antiproton bunches footprint (blue)
Proton bunches footprint (orange)

…operationally it is even more complicated!
…intensities differences, emittances diff…

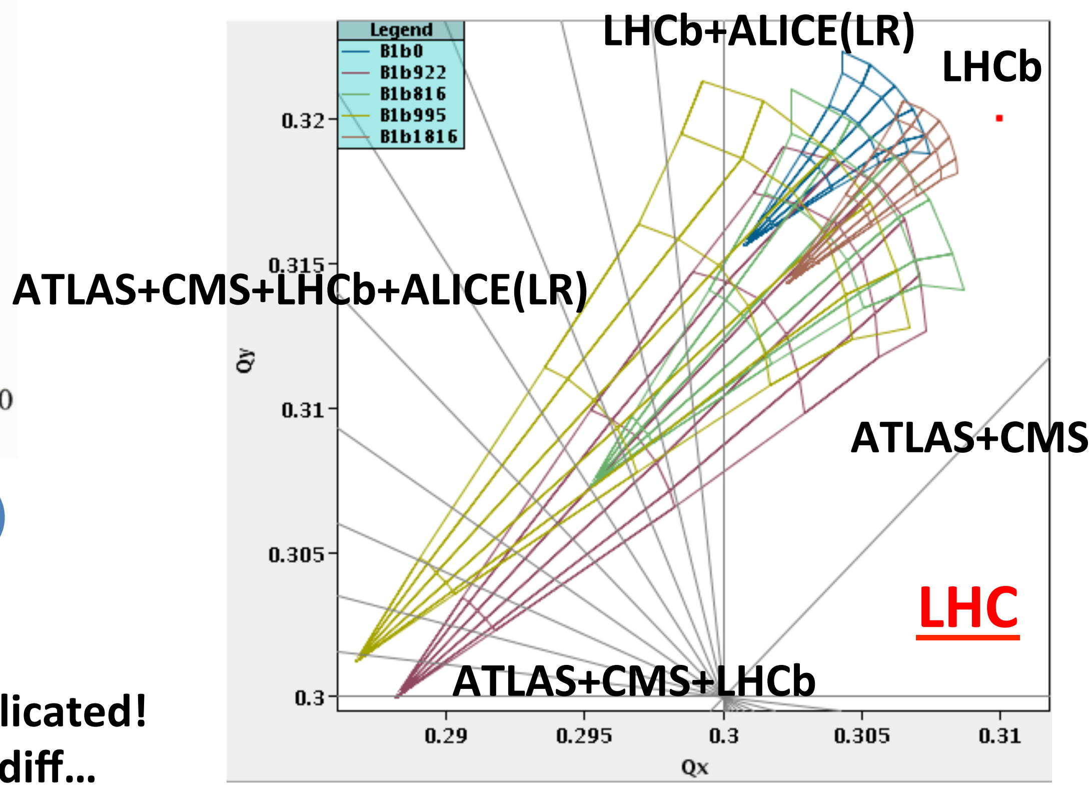
Pacman and Super-pacman



Tevatron



Antiproton bunches footprint (blue)
Proton bunches footprint (orange)



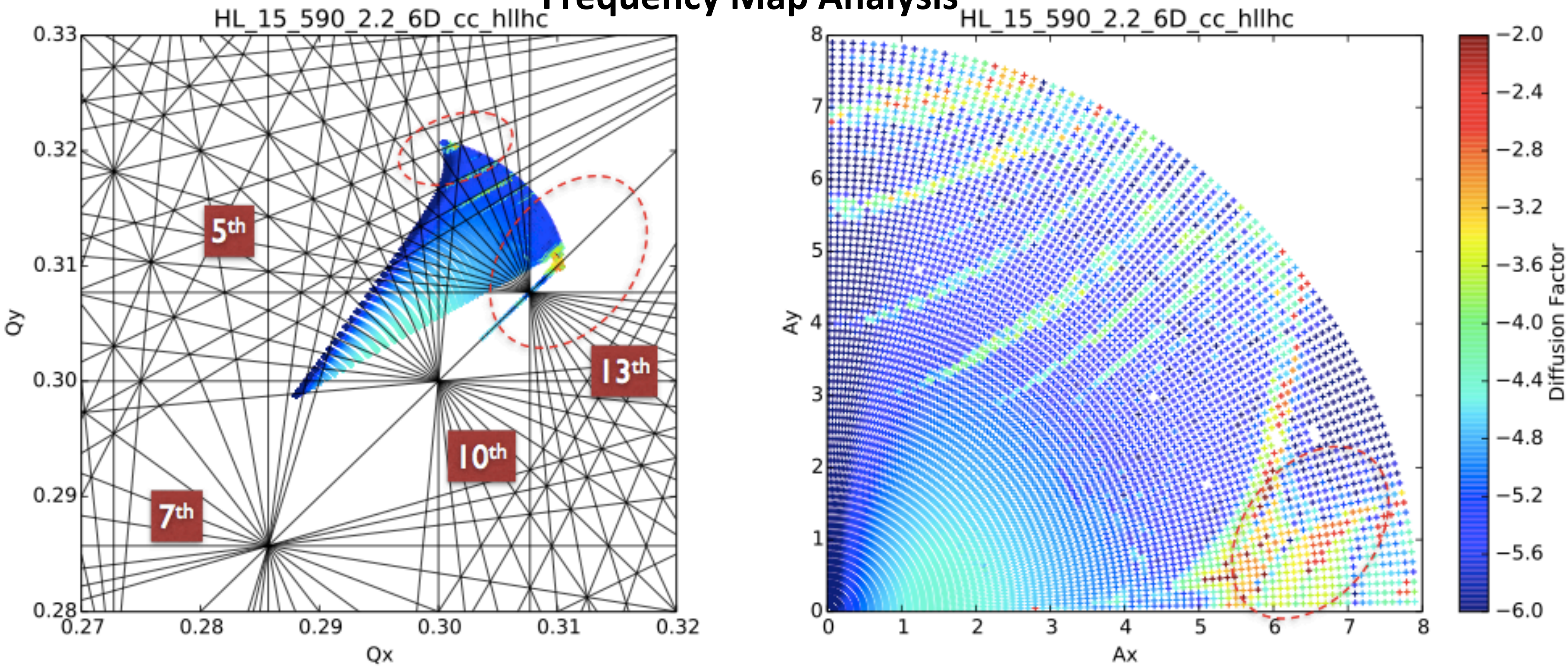
…operationally it is even more complicated!
…intensities differences, emittances diff…

Non-linear dynamics and Particle Losses

Dynamic Aperture: area in amplitude space with stable motion

Stable area of particles depends on beam intensity and crossing angle

Frequency Map Analysis



Stable area depends on beam-beam interactions therefore the choice of running parameters (crossing angles, β^*, intensity) is the result of careful study of different effects!

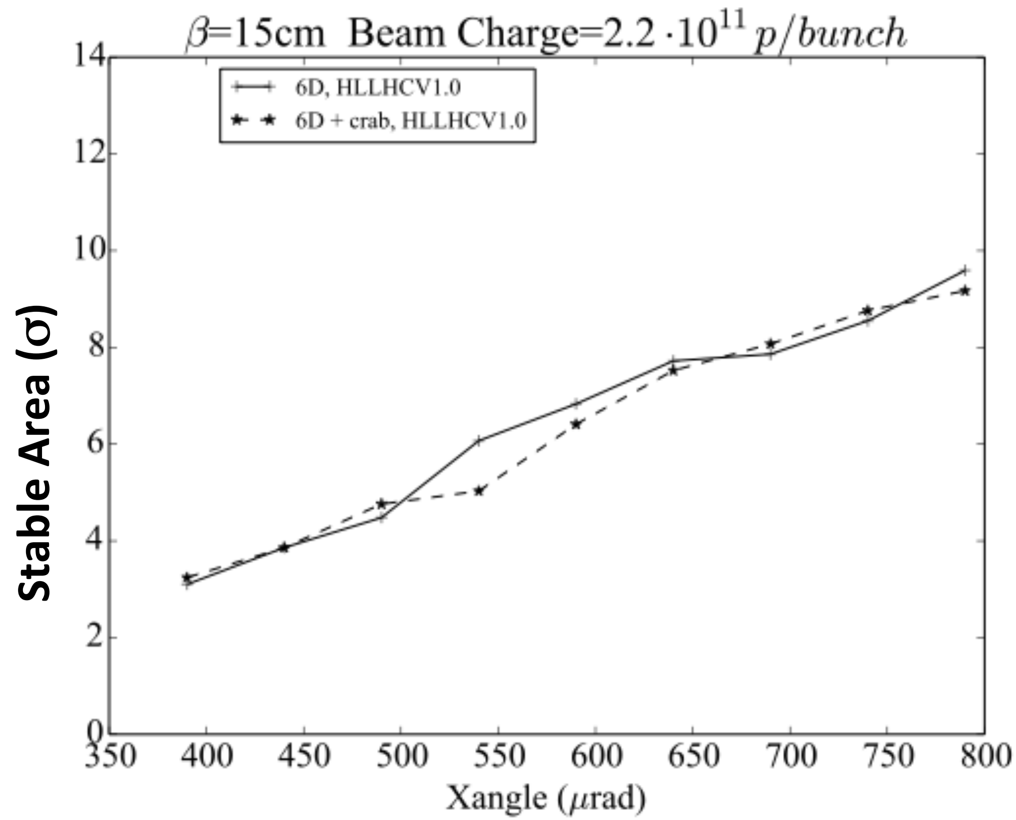
Ref [6]

Non-linear dynamics and Particle Losses

Dynamic Aperture: area in amplitude space with stable motion

Stable area of particles depends on beam intensity and crossing angle

$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$



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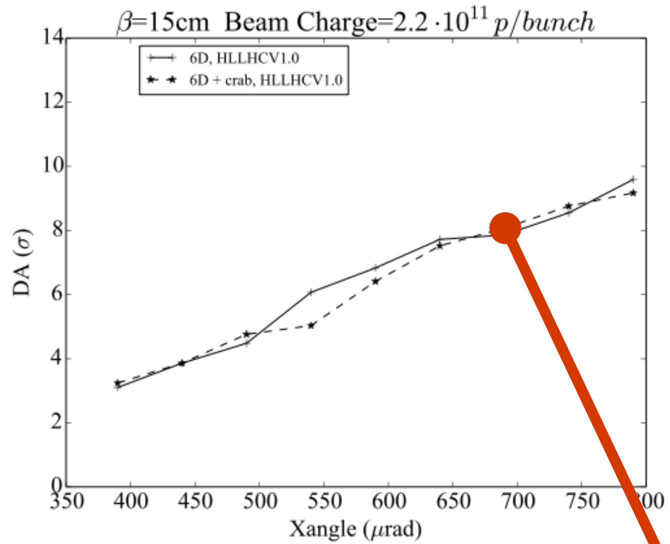
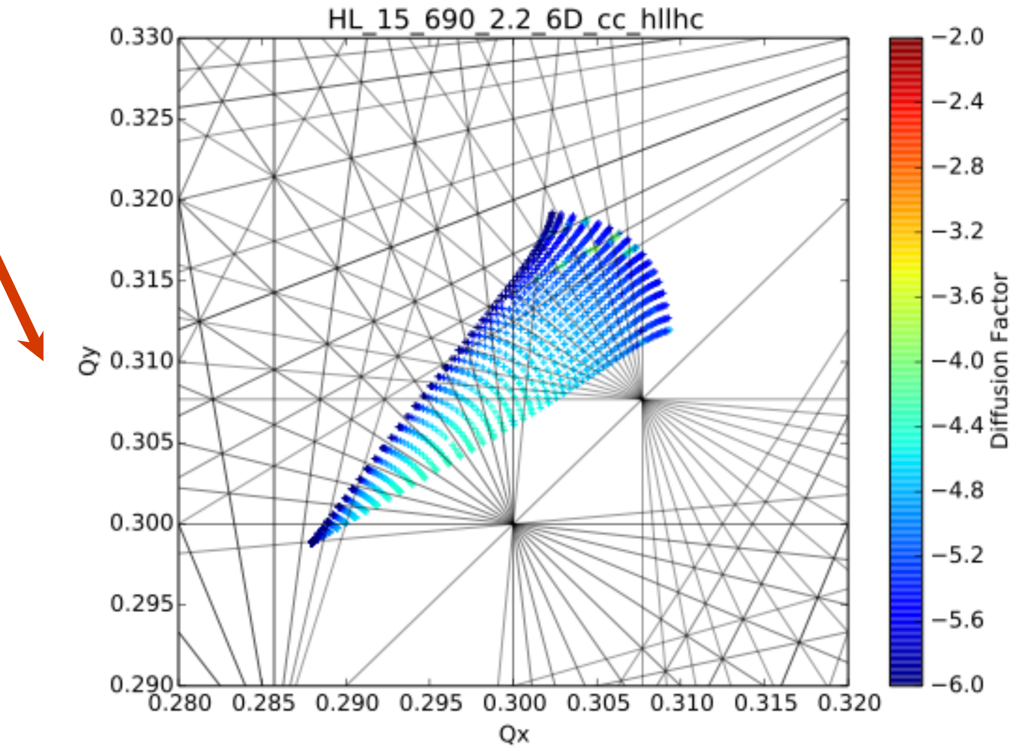
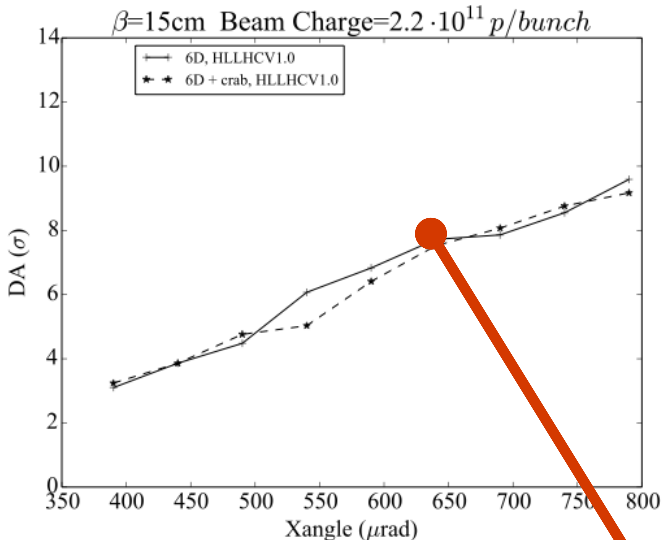
Ref [6]

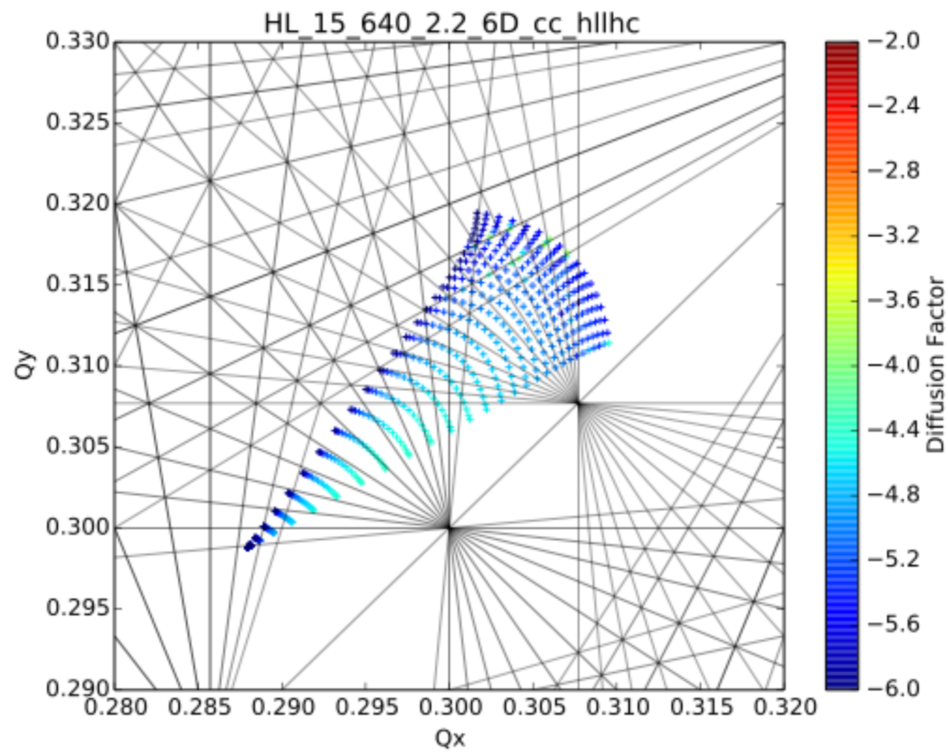
Non-linear dynamics and Particle Losses



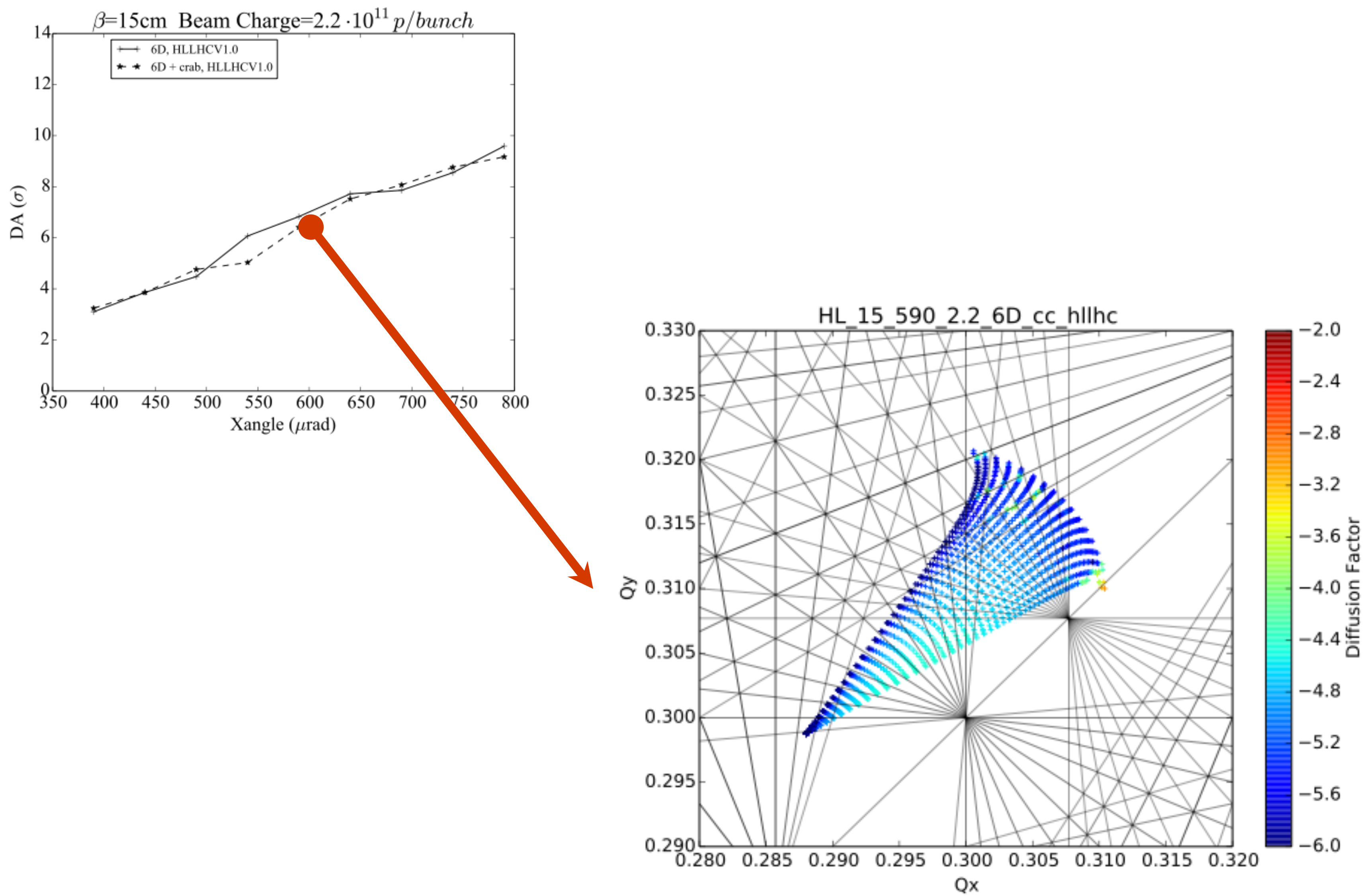


Non-linear dynamics and Particle Losses

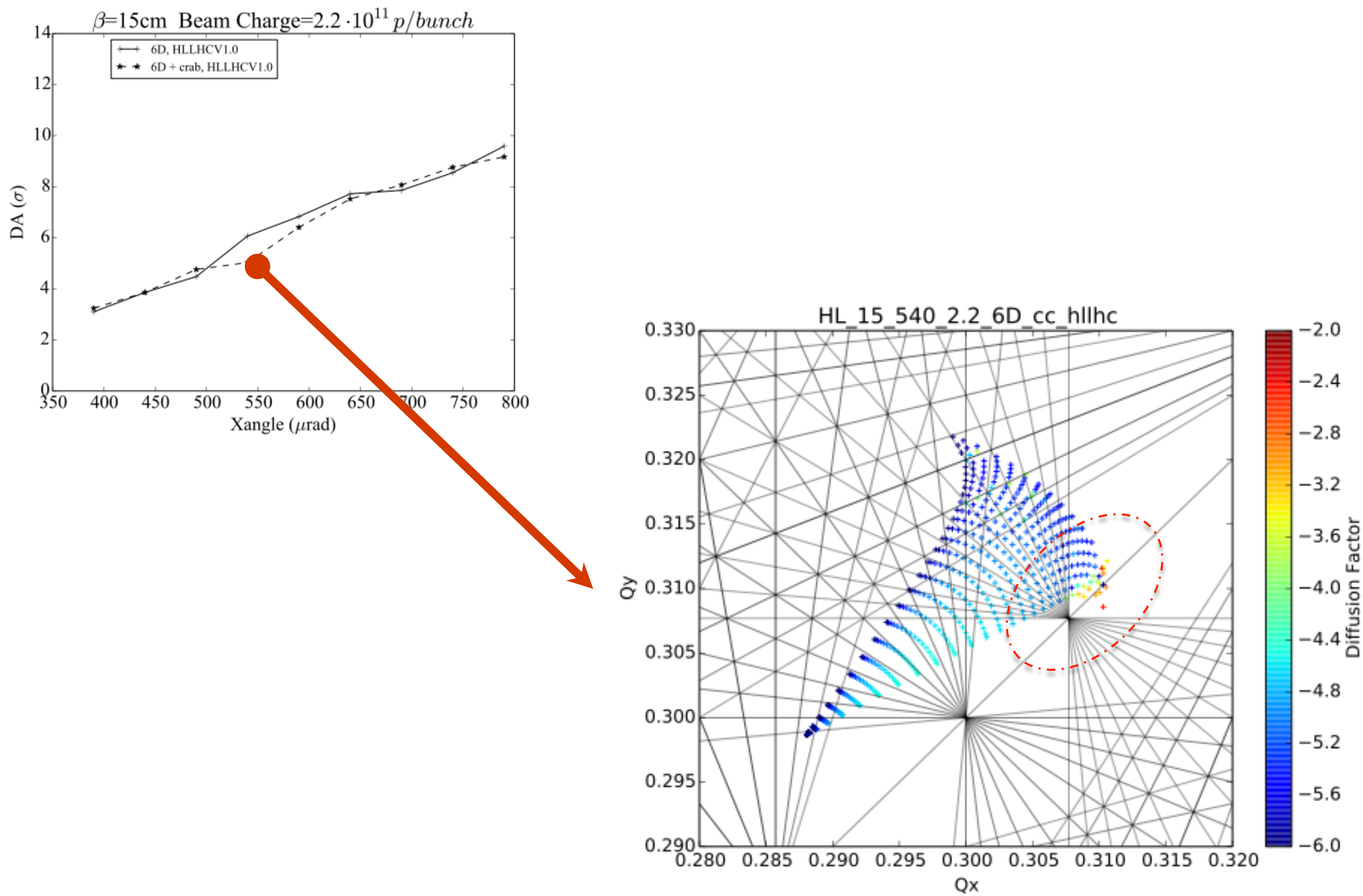




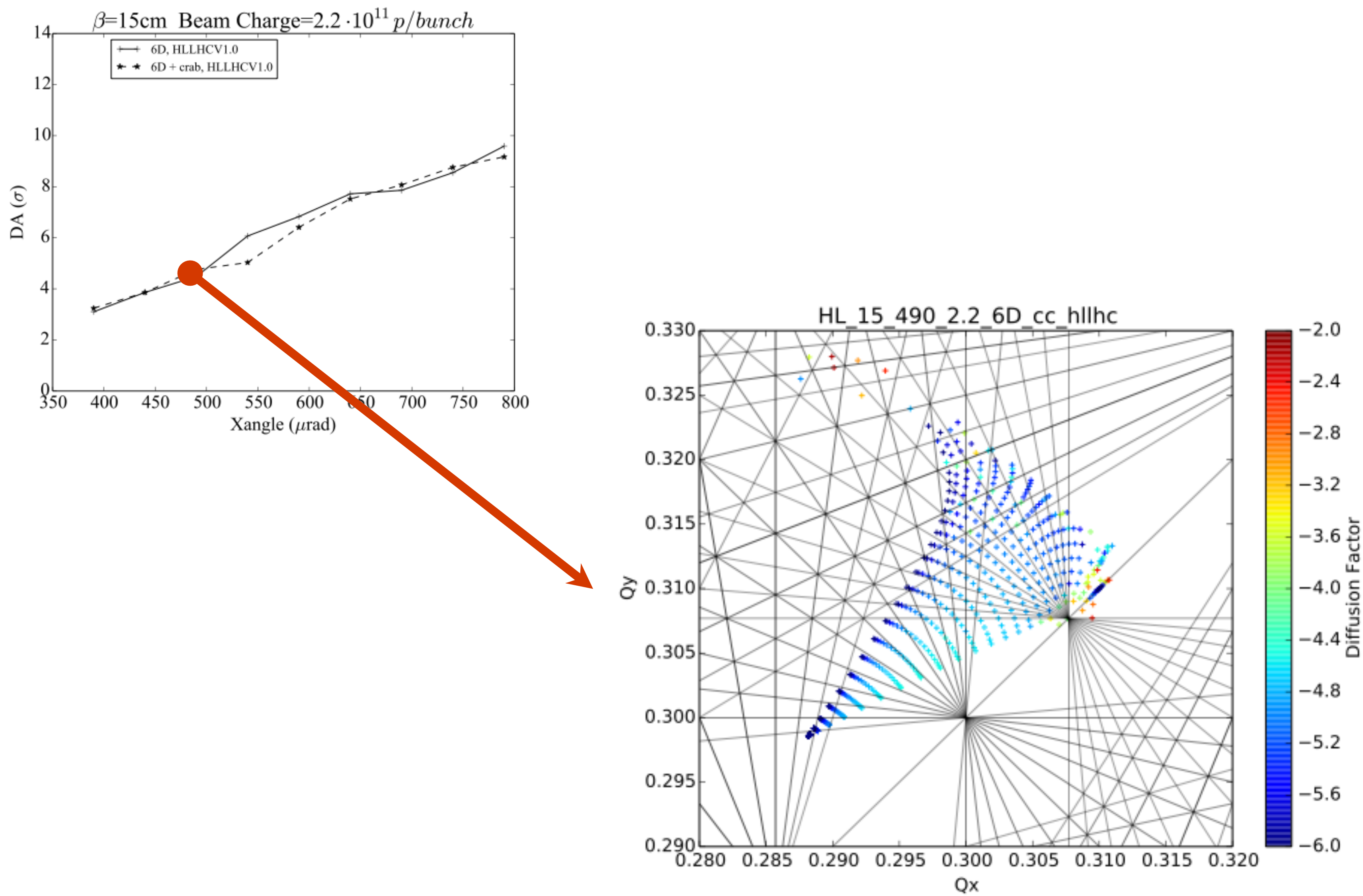
Non-linear dynamics and Particle Losses



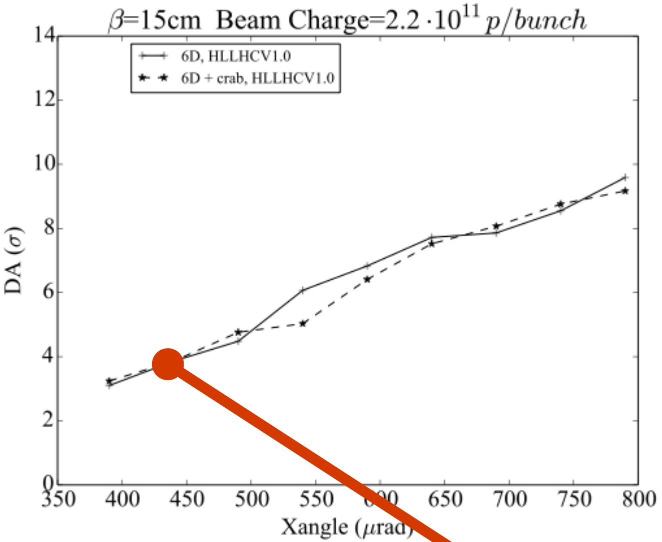
Non-linear dynamics and Particle Losses



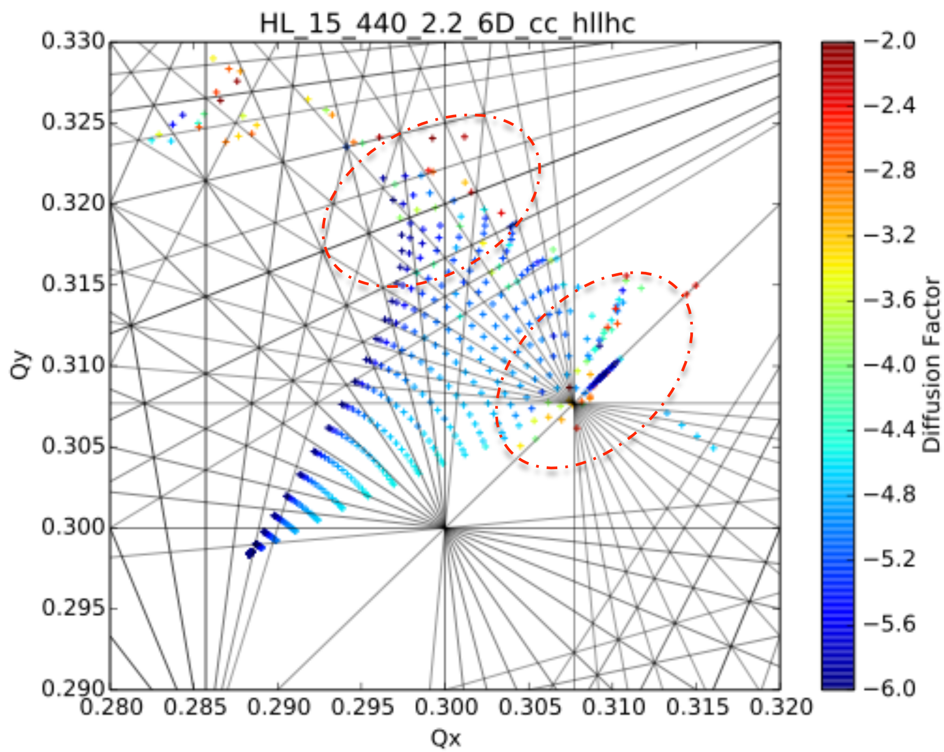
Non-linear dynamics and Particle Losses



Non-linear dynamics and Particle Losses



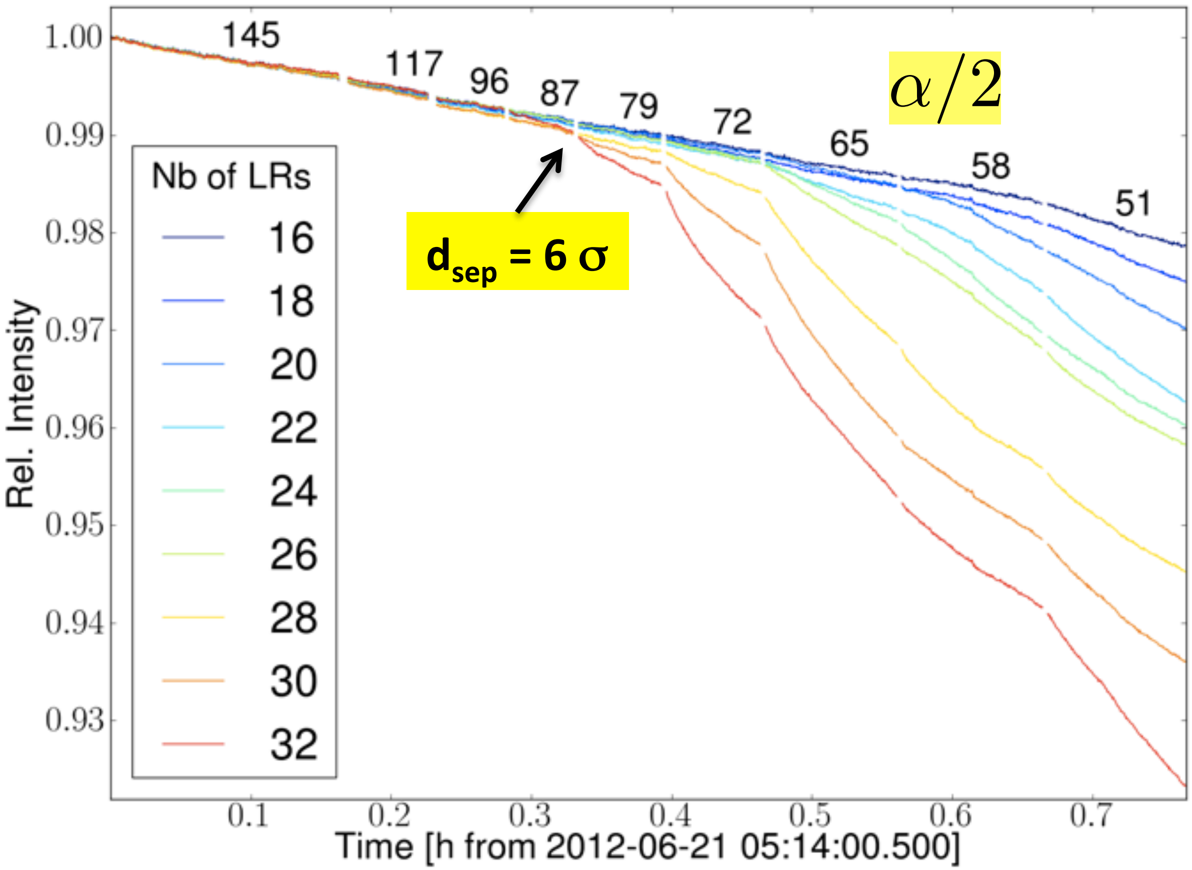
Crossing angle changes the separation and the strength of BB-LR that strongly affect the tails. 0σ particle are almost not affected.



At small separation particles gets unstable and eventually lost

Non-linear dynamics and Particle Losses

Bunch losses for different families of Long-Range encounters



Beam-Beam separation at first LR

$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon}}$$

At small separations particles motion becomes chaotic and particles are eventually lost.

The loss rate depends on number of long range encounters and beam-beam parameter

The on-set of losses and the loss rates can be related to dynamic aperture

Long-range BB and Orbit Effects

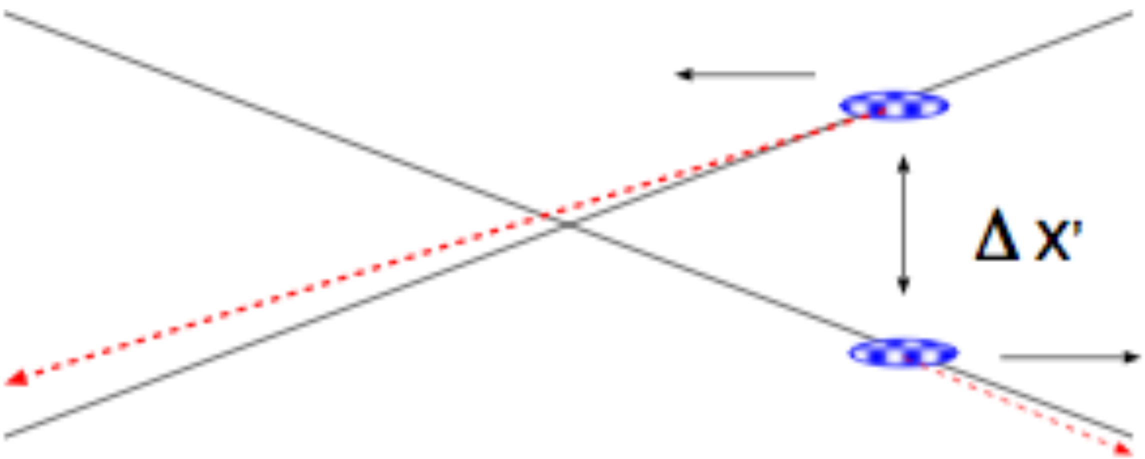
Long Range Beam-beam interactions lead to orbit effects

Long range kick $$\Delta x'(x+d,y,r) = -\frac{2Nr_0}{\gamma}\frac{(x+d)}{r^2}[1-\exp(-\frac{r^2}{2\sigma^2})$$

For well separated beams $d \gg \sigma$

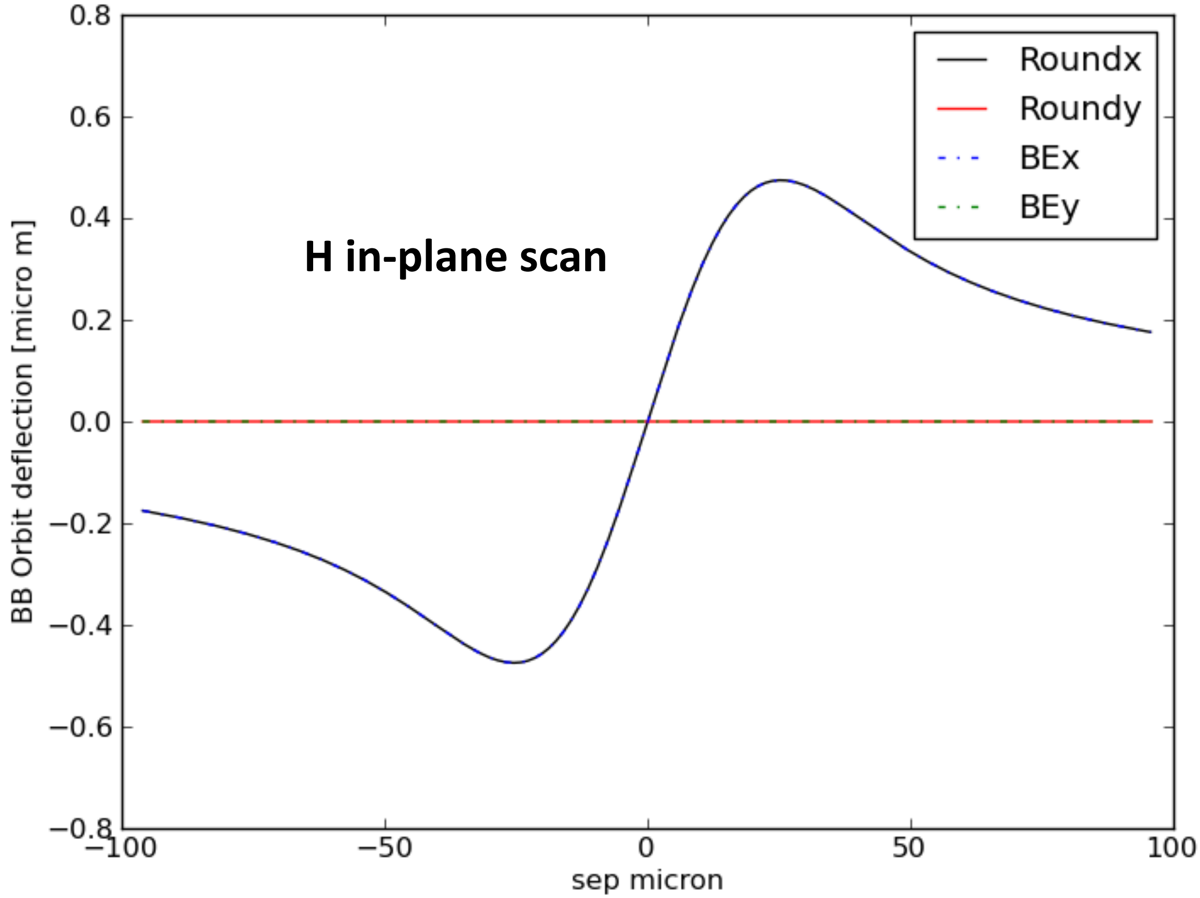
The force has an amplitude independent contribution: ORBIT KICK

$$\Delta x' = \frac{const}{d}[1 - \frac{x}{d} + O(\frac{x^2}{d^2}) + \ldots]$$



Orbit can be corrected but we should remember PACMAN effects

Orbit effect as a function of separation



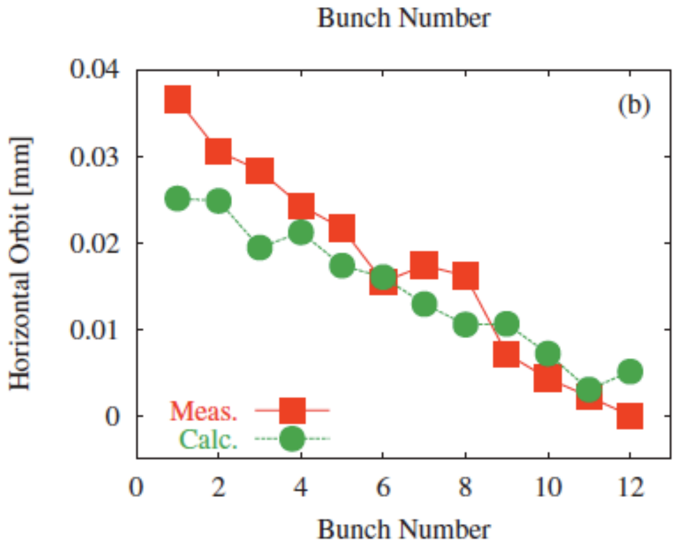
Angular Deflections:

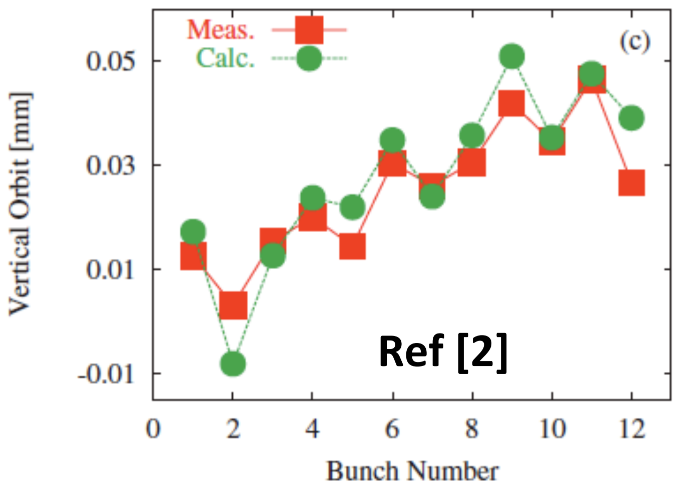
$$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

Closed Orbit effect:

$$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

Tevatron orbit effects

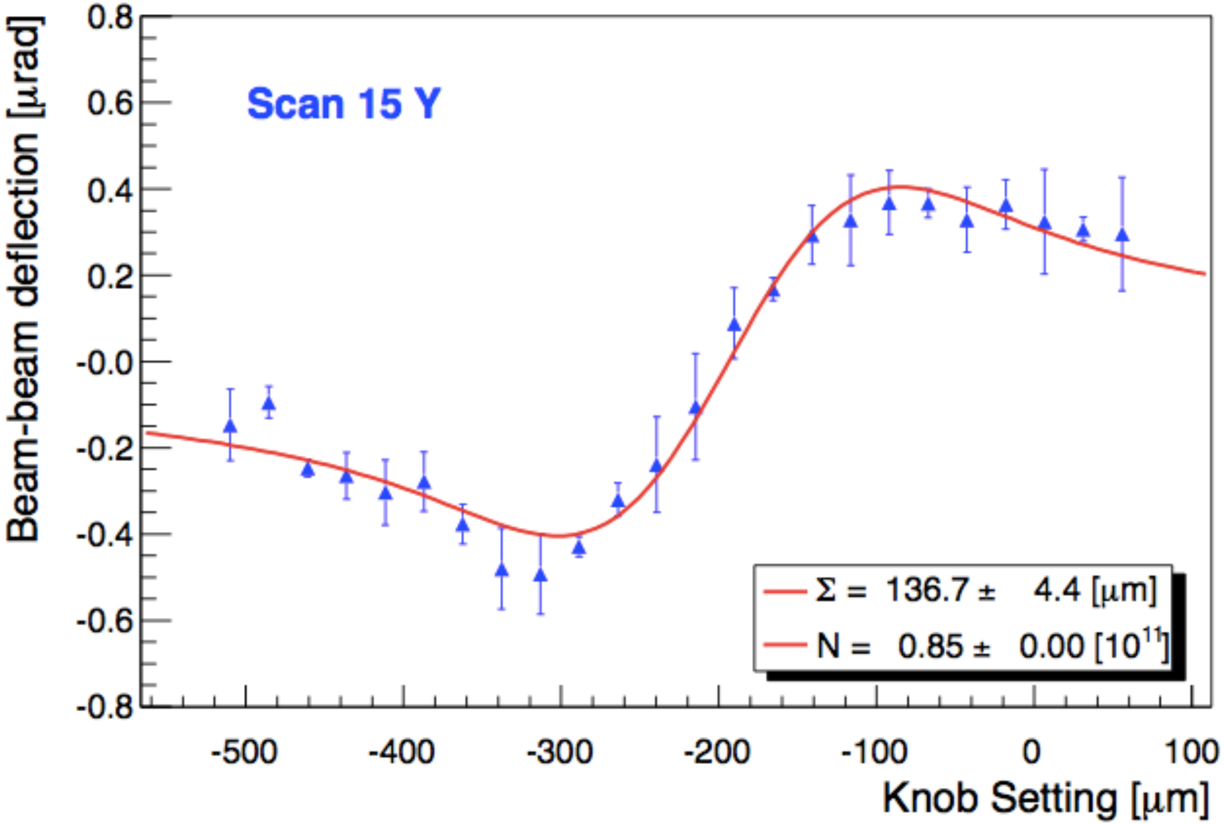




Beam-beam single bunch orbit can be well reproduced and measured also in LEP

Effects can become important (1 σ offset not impossible)

Orbit effect as a function of separation



Angular Deflections: $$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

Closed Orbit effect: $$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$

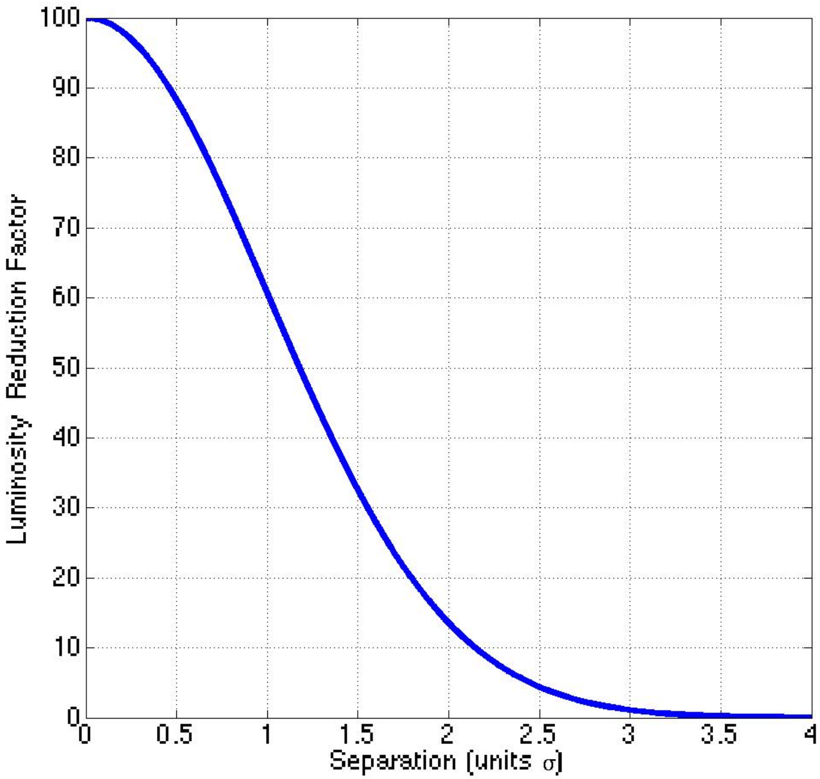
Orbit can be corrected but we should remember PACMAN effects

LHC observations

Many long range interactions could become important effect!

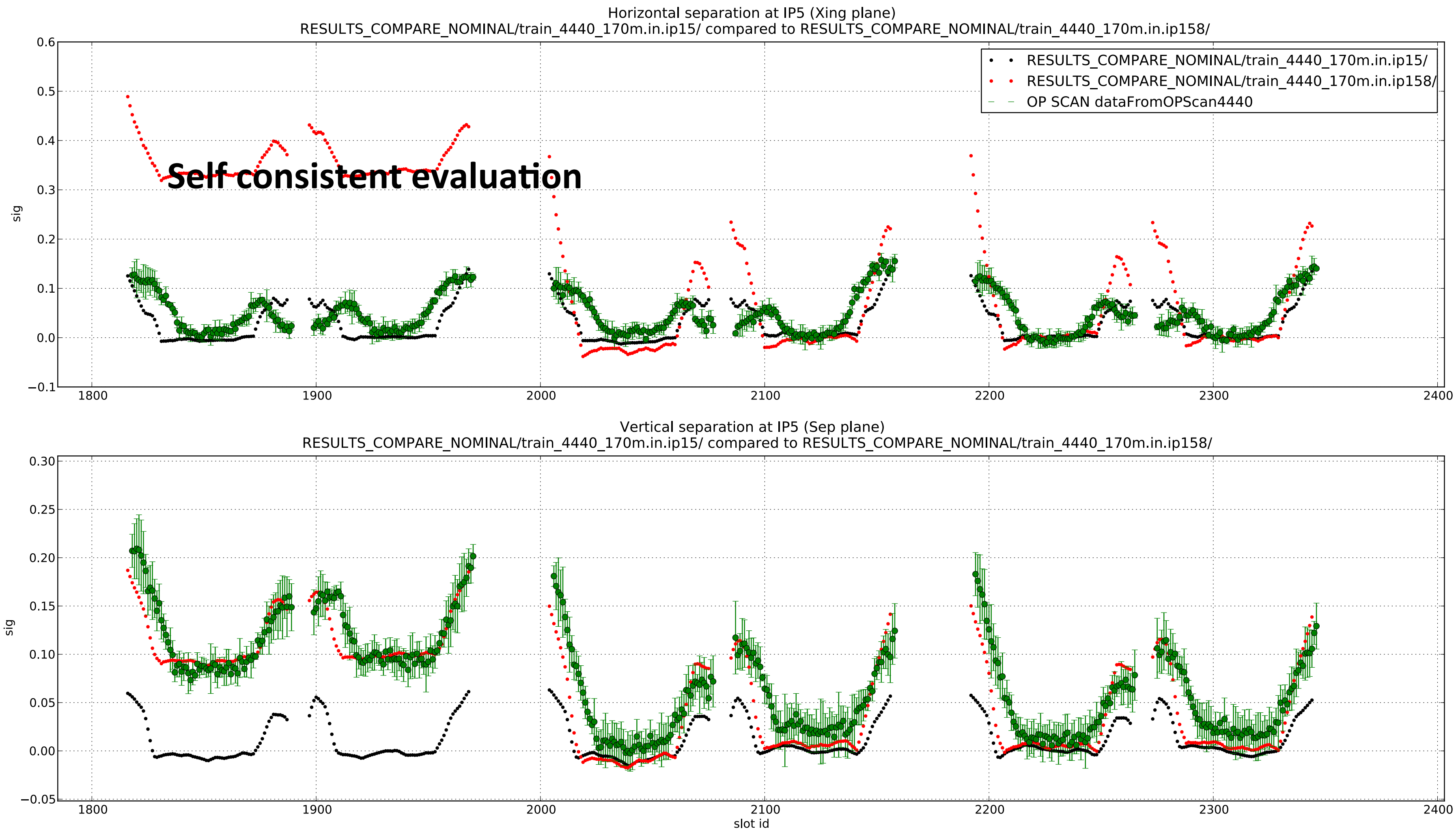
Holes in bunch structure leads to PACMAN effects this cannot be corrected!

$$L = L_0 \cdot e^{-\frac{d^2}{4\sigma_x^2}}$$



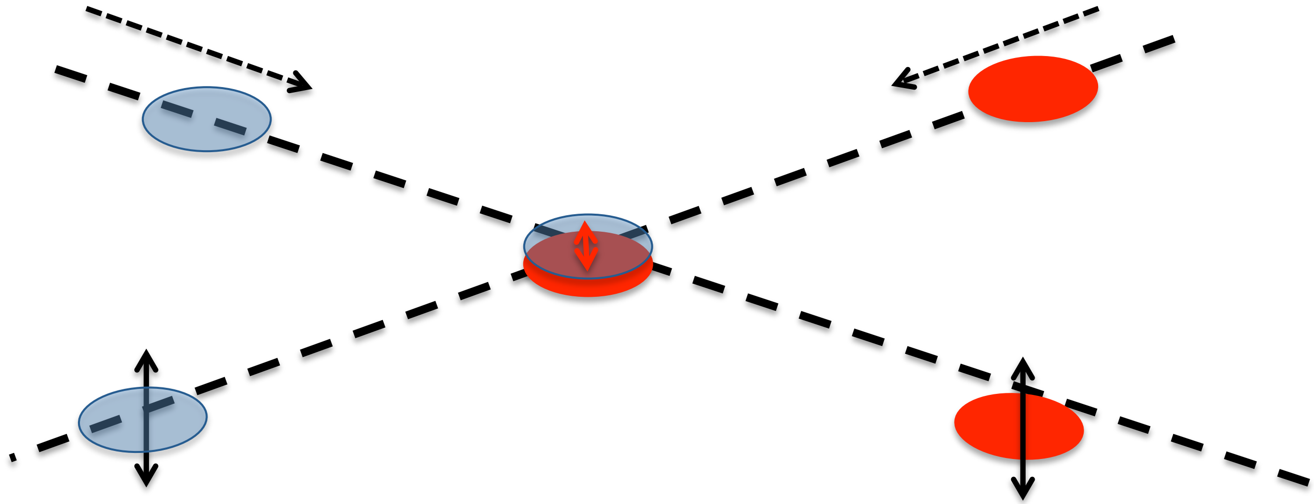
Orbit Effects due to long-range beam-beam effects should be kept SMALL to avoid loss of luminosity!

LHC observations vs simul



LUMINOSITY Deterioration

Coherent beam-beam effects



- Whole bunch sees a kick as an entity (coherent kick)
- Coherent kick seen by full bunch different from single particle kick
- Requires integration of individual kick over particle distribution

$$\Delta r' = -\frac{N_p r_0}{r} \cdot \frac{r}{r^2} \cdot \left[1 - \mathrm{e}^{-\frac{r^2}{4\sigma^2}}\right]$$

- Coherent kick of separated beams can excite coherent dipolar oscillations
- All bunches couple because each bunch "sees" many opposing bunches(LR): many coherent modes possible!

Coherent effects

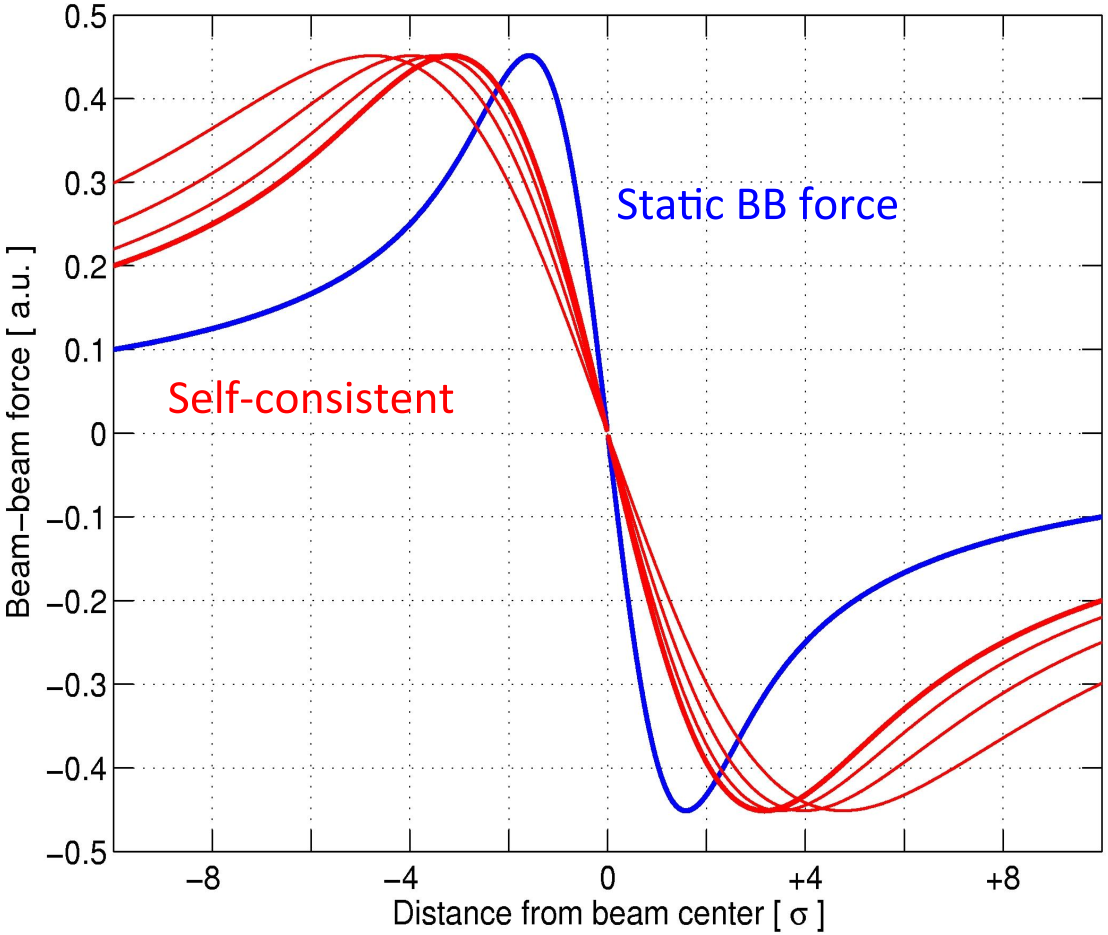
Self-consistent treatment needed

Perturbative methods

static source of distortion:
example magnet

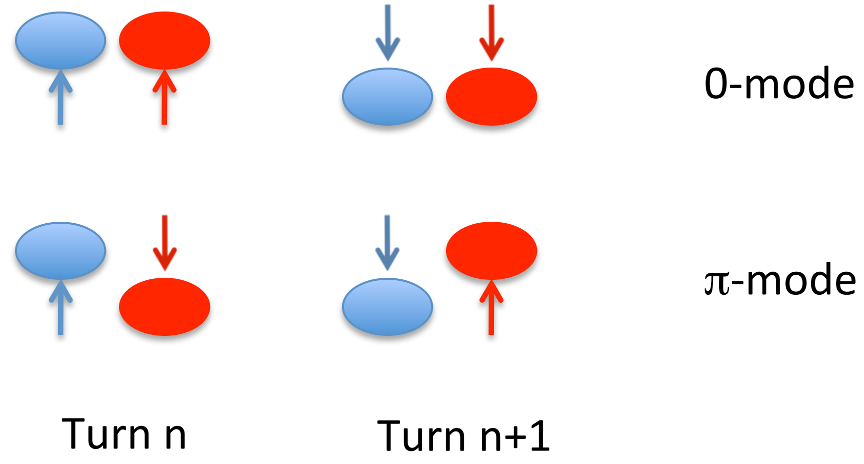
Self-consistent method

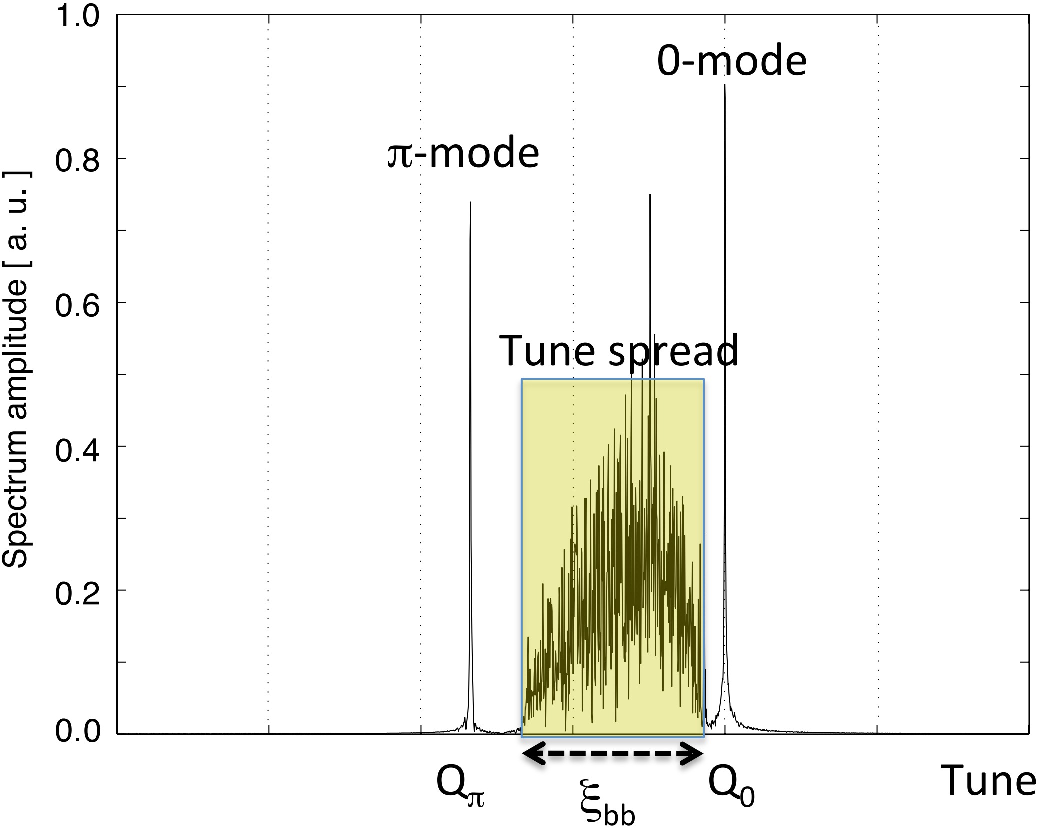
source of distortion changes
as a result of the distortion



For a complete understanding of BB effects a self-consistent treatment is necessary

Head-on coherent modes





0-mode at unperturbed tune Q_0

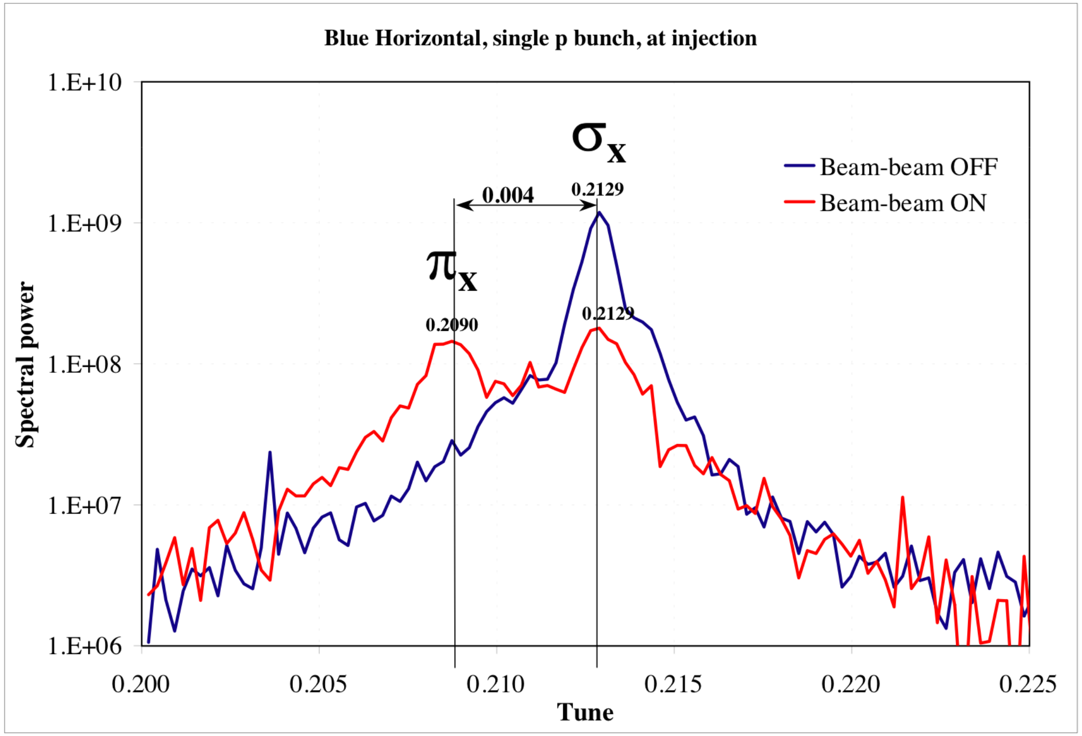
π-mode is shifted at Q_π =1.1-1.3 ξ_{bb}

Incoherent tune spread range [0,-ξ]

$$\Delta Q = Y \cdot \xi$$

- Coherent mode: two bunches are “locked” in a coherent oscillation
- 0-mode is stable (mode with NO tune shift)
- π-mode can become unstable (mode with largest tune shift)

Coherent modes at RHIC

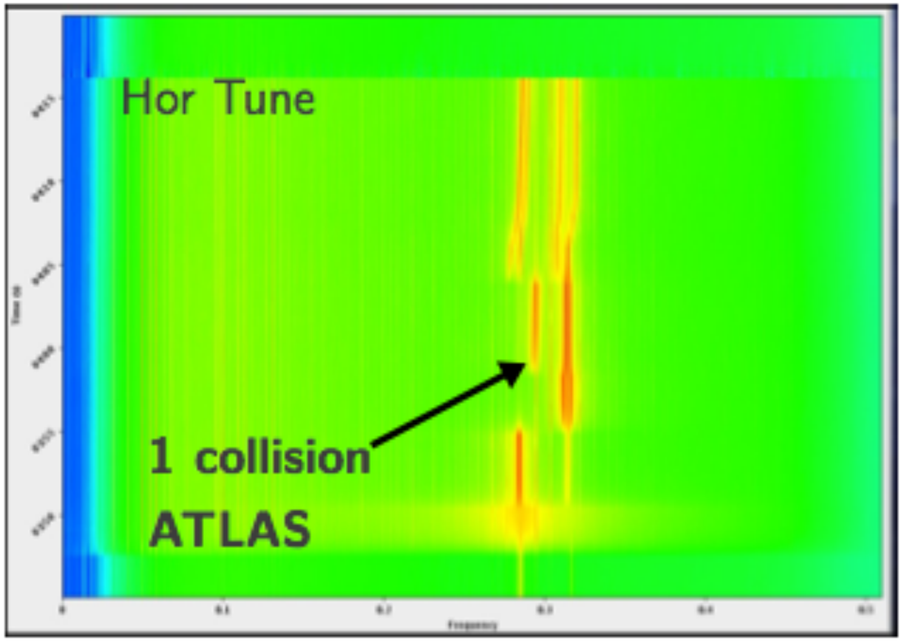


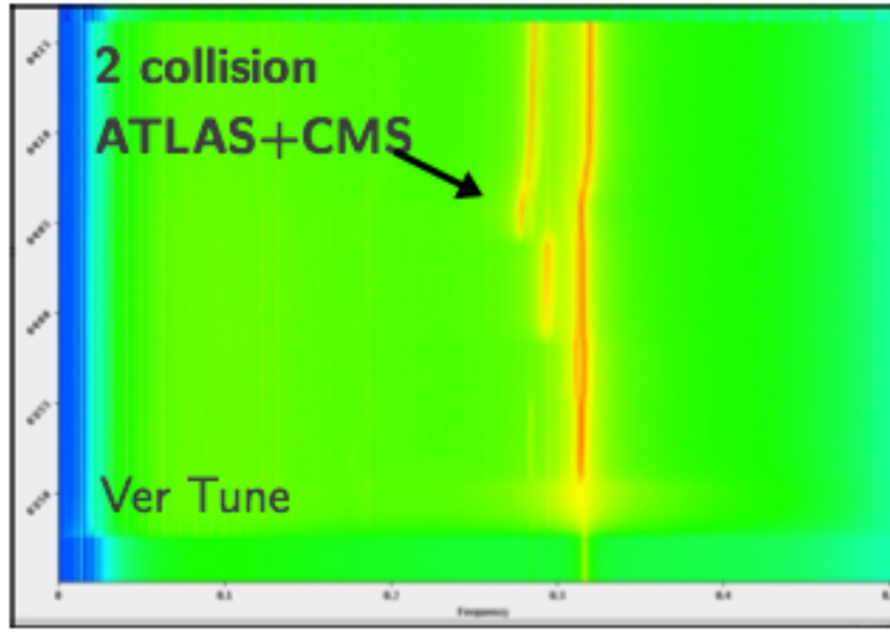
Courtesy W. Fischer (BNL)

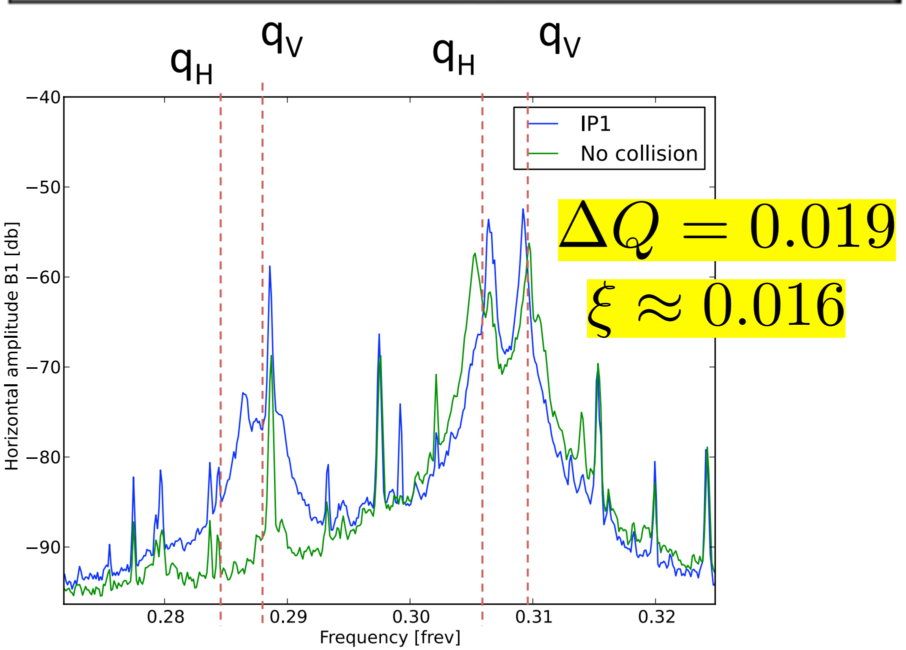
Tune spectra before collision and in collision two modes visible

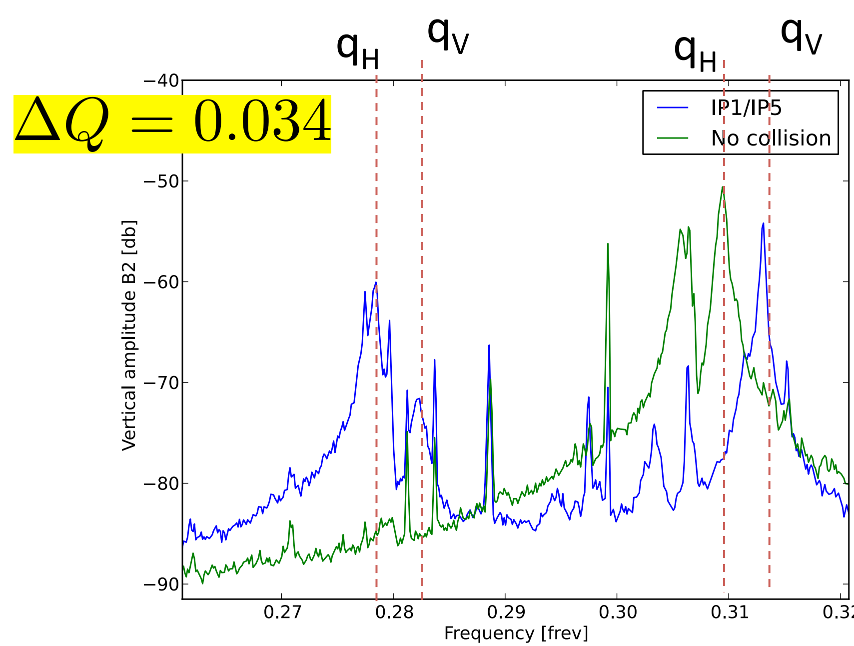
Head-on beam-beam coherent modes in the LHC

BBQ Signals



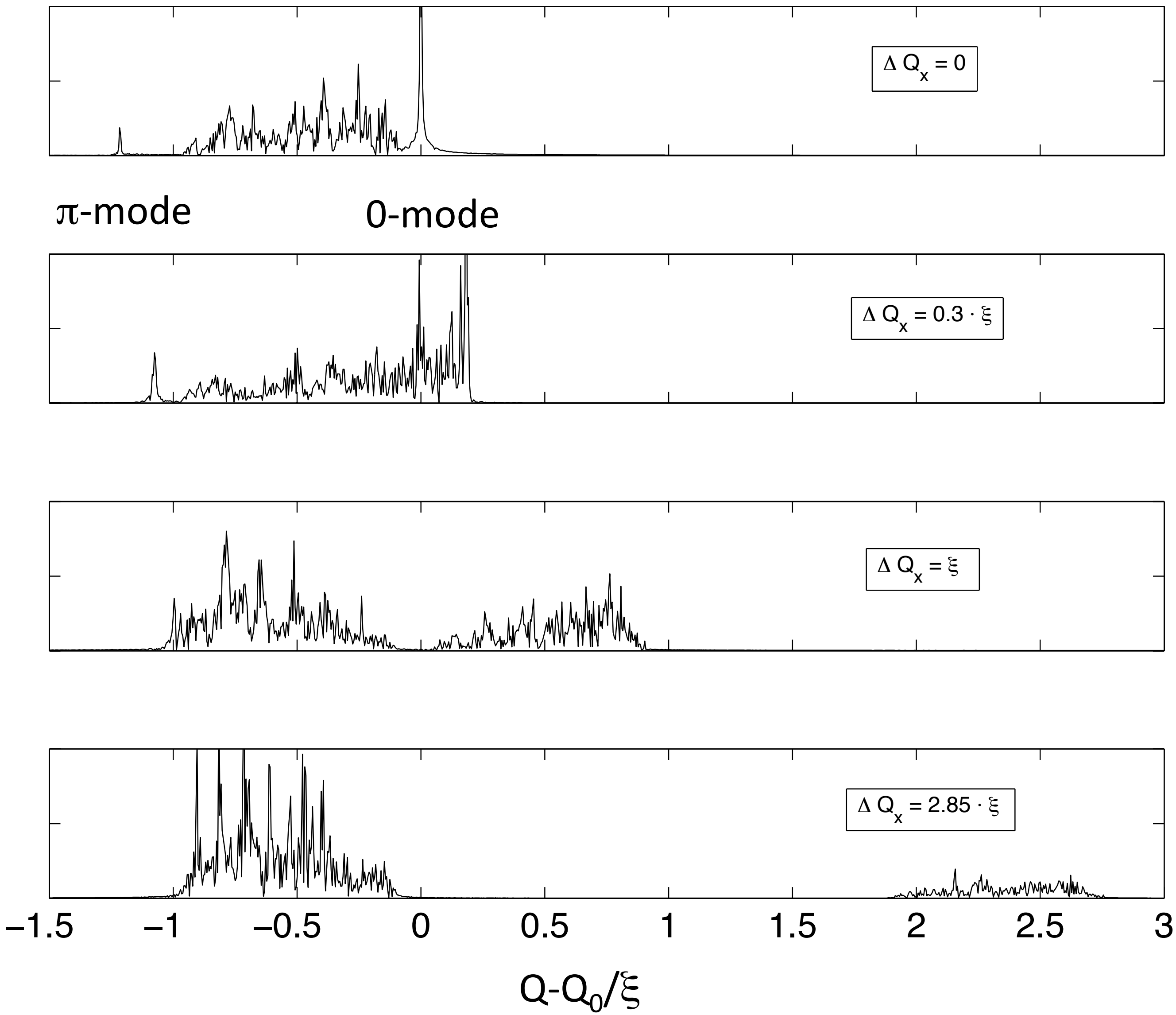






Breaking of coherent motion: Tune split

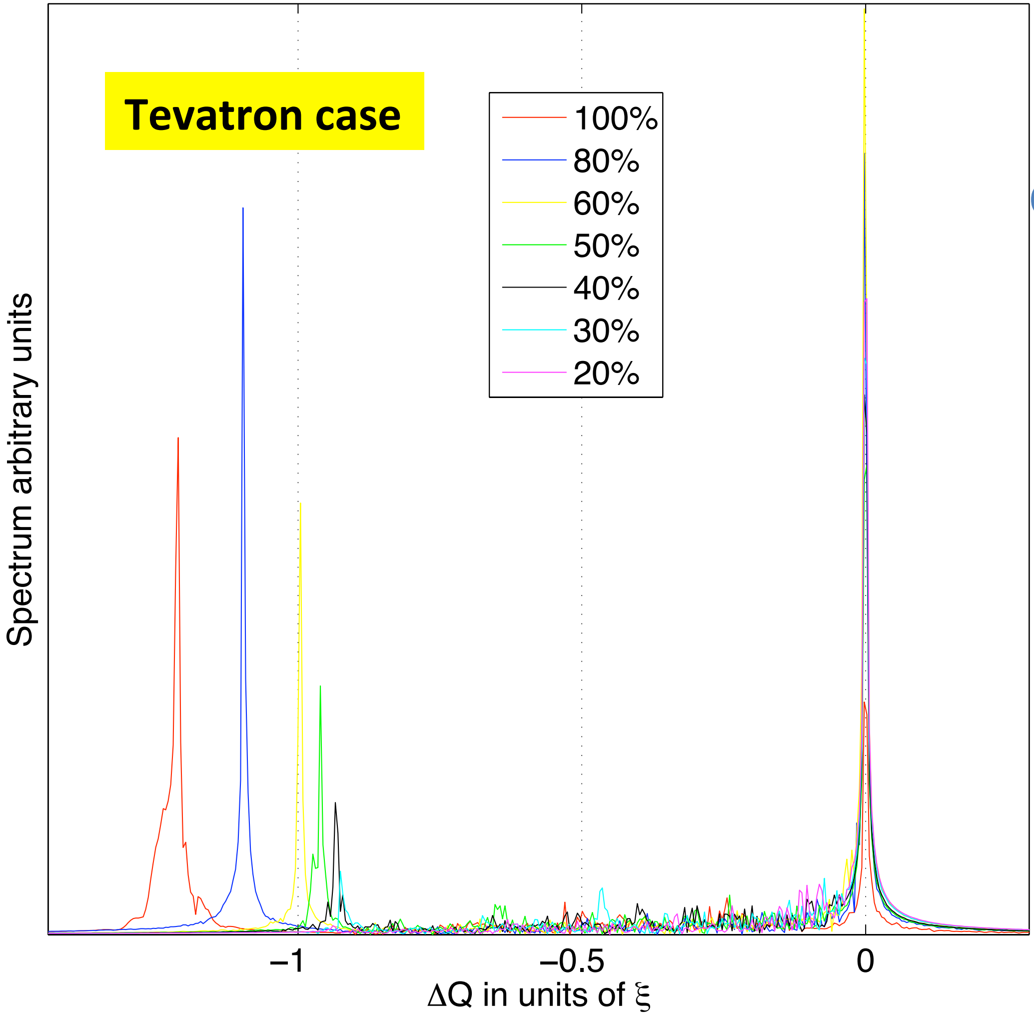
RHIC case



Tune split breaks symmetry and coherent modes disappear

Analytical calculations in Reference [8]

Breaking of coherent motion: Intensity ratio



For two bunches colliding head-on in one IP the coherent mode disappears if intensity ratio between bunches is 55% **Reference[9]**

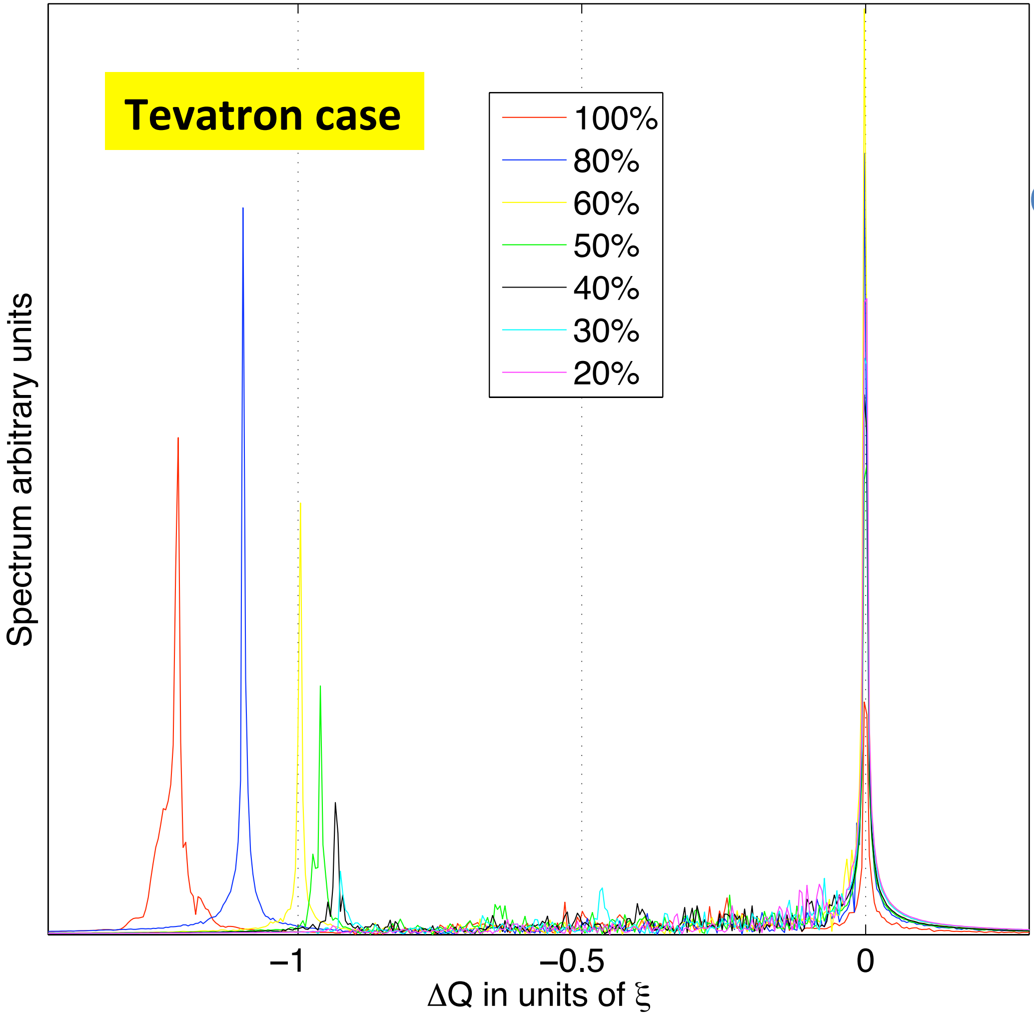
We assumed:

- equal emittances
- equal tunes
- NO PACMAN effects

(bunches will have different tunes)

For coherent modes the key is to break the simmetry in your coupled system…(tunes, intensities, collision patters, …)!

Breaking of coherent motion: Intensity ratio



For two bunches colliding head-on in one IP the coherent mode disappears if intensity ratio between bunches is 55% **Reference[9]**

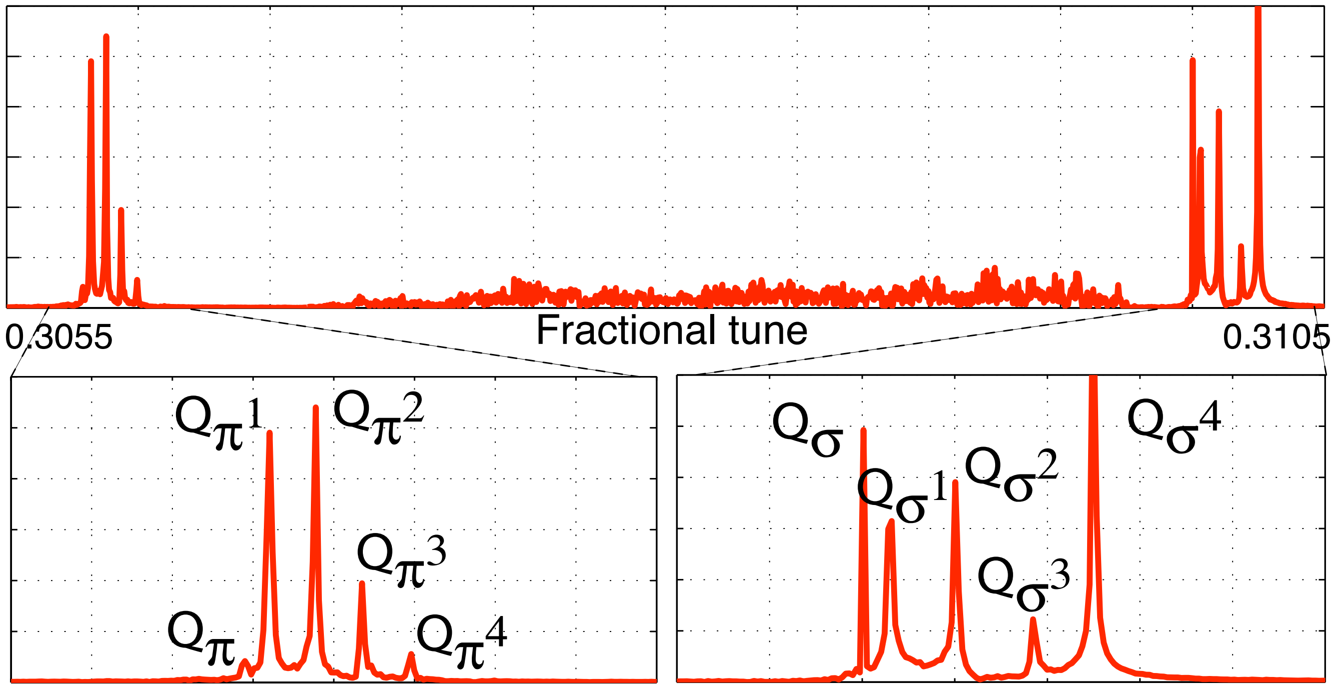
We assumed:

- equal emittances
- equal tunes
- NO PACMAN effects

(bunches will have different tunes)

or to merge the modes into the incoherent spread!

Long-range coherent modes

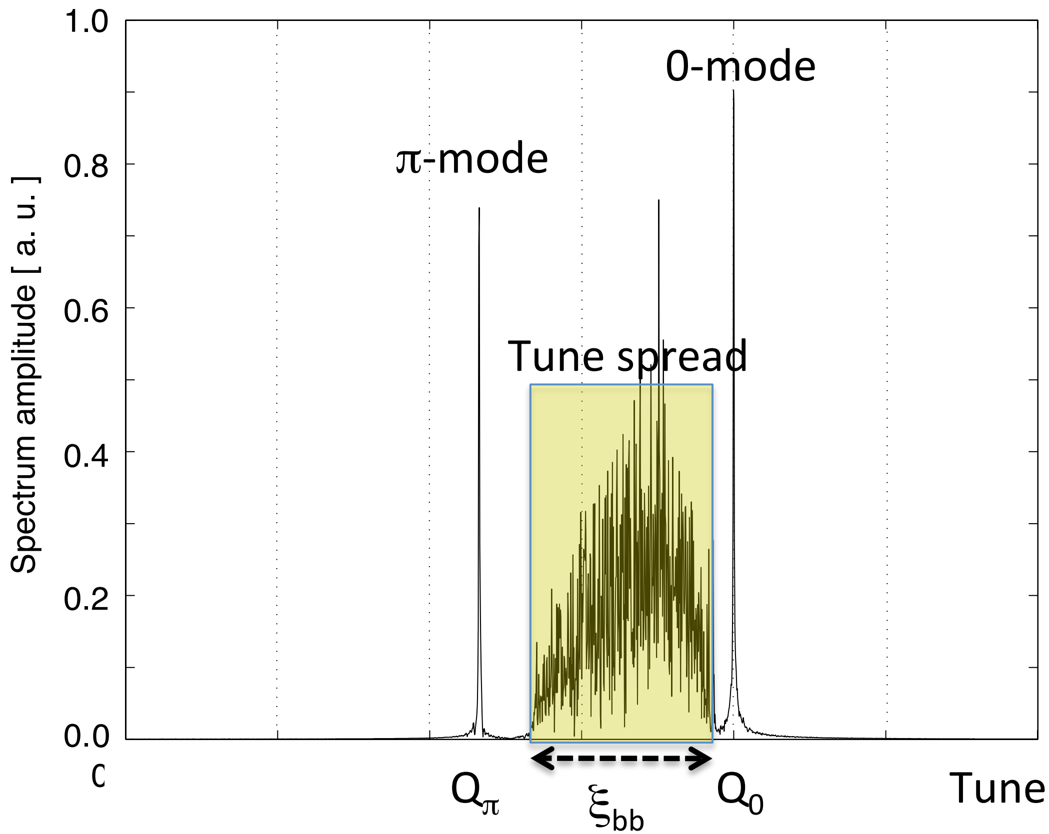


Pacman bunch will have different number of modes

Could drive instabilities if coupled to impedance driven modes…

Cannot be damped by incoherent spread…!

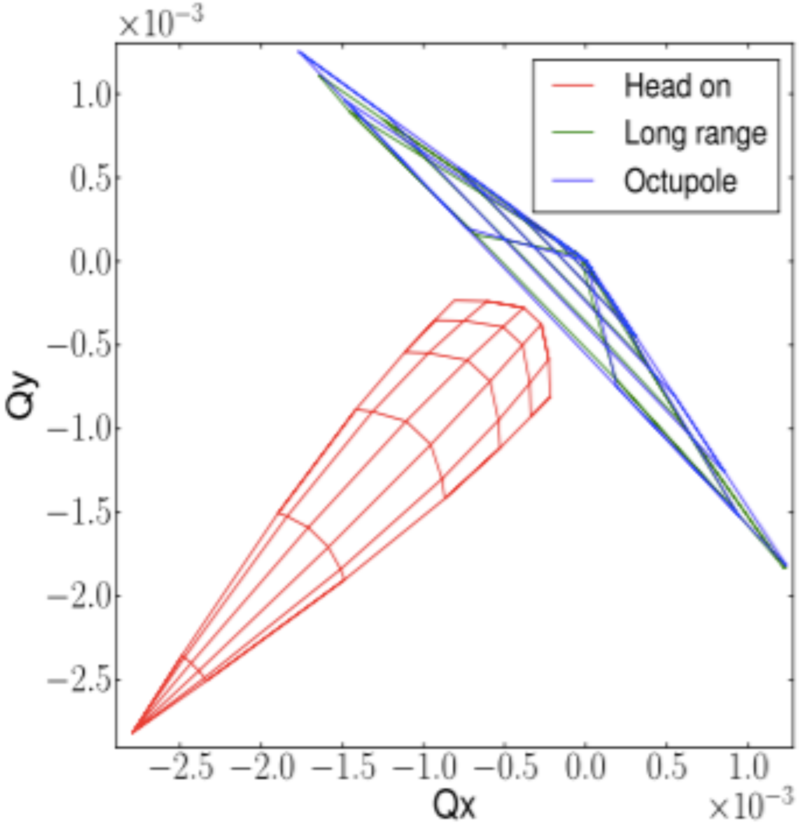
Landau damping

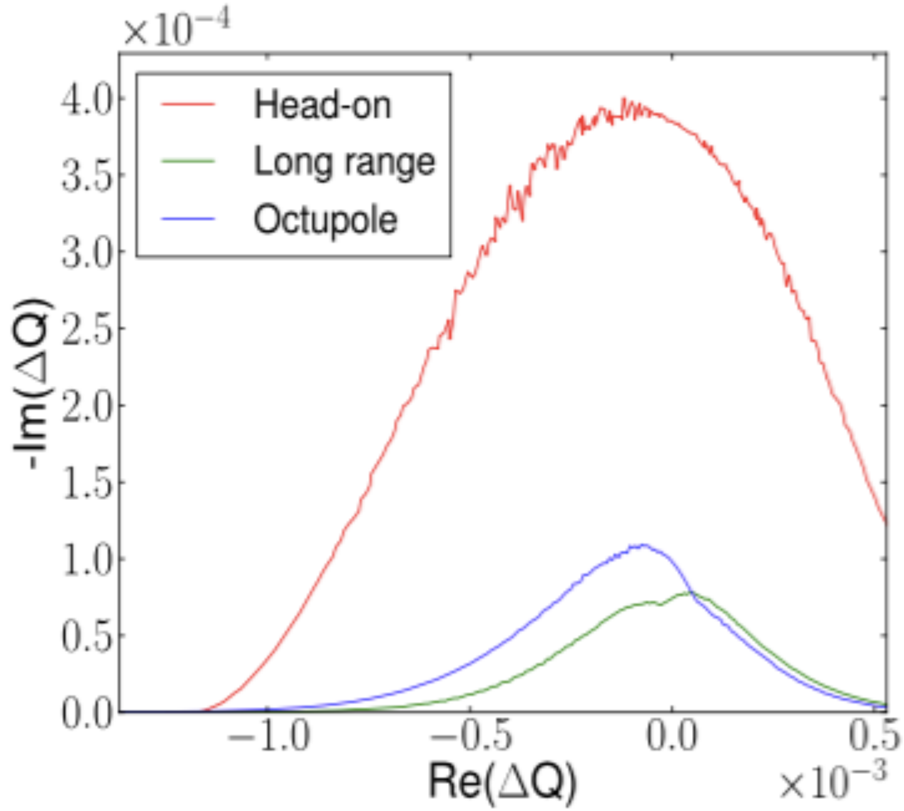


Incoherent tune spread is the Landau damping region any mode with frequency laying in this range should not develop

Tune spread positive effects: Landau damping

See Kornilov lecture



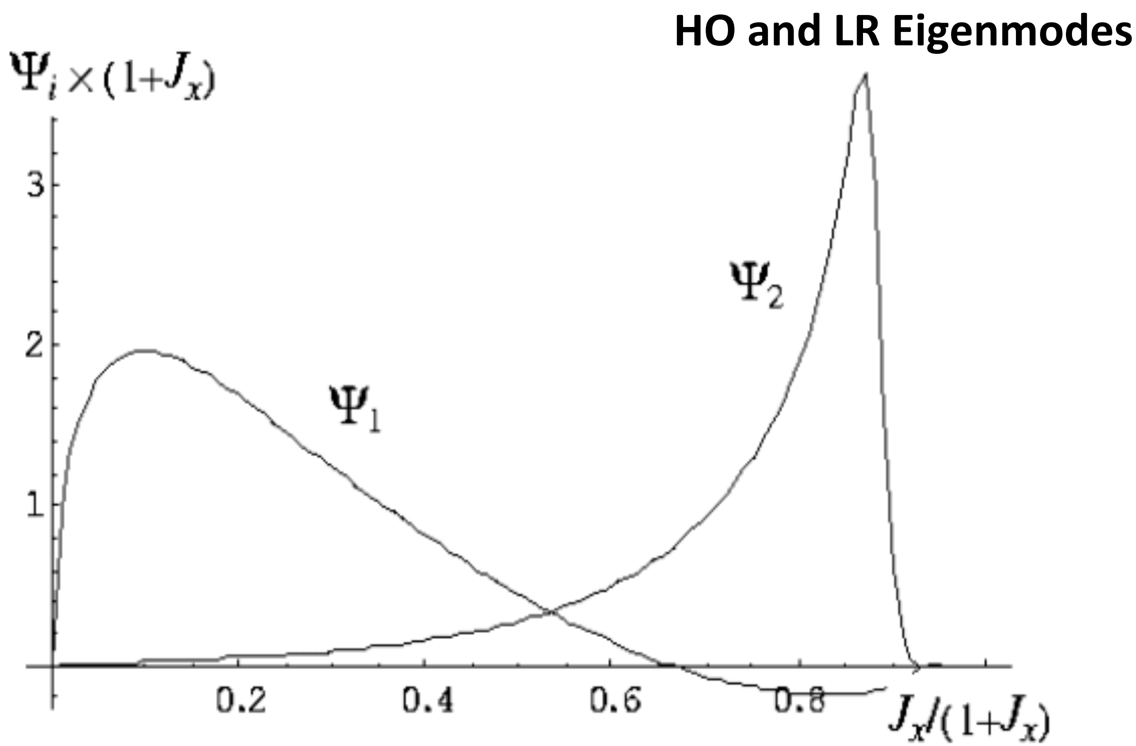


Head-on spread and Landau damping most effective if compared to octupoles or long-range spreads.

Effective to damp impedance and head-on beam-beam modes!

Cannot damp long-range modes!

Tune spread positive effects: Landau damping



Ref[12]

Different particles are involved in the coherent motion and in the Landau damping…

HO modes are due to core particle oscillation as the spread→ Landau damping effective!

LR modes are due to bunch tails oscillations → NO Landau damping!

Special observation in Leptons

From our known formulas:

$$L = \frac{N_1 N_2 f n_b}{4\pi\sigma_x\sigma_y} \qquad \xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

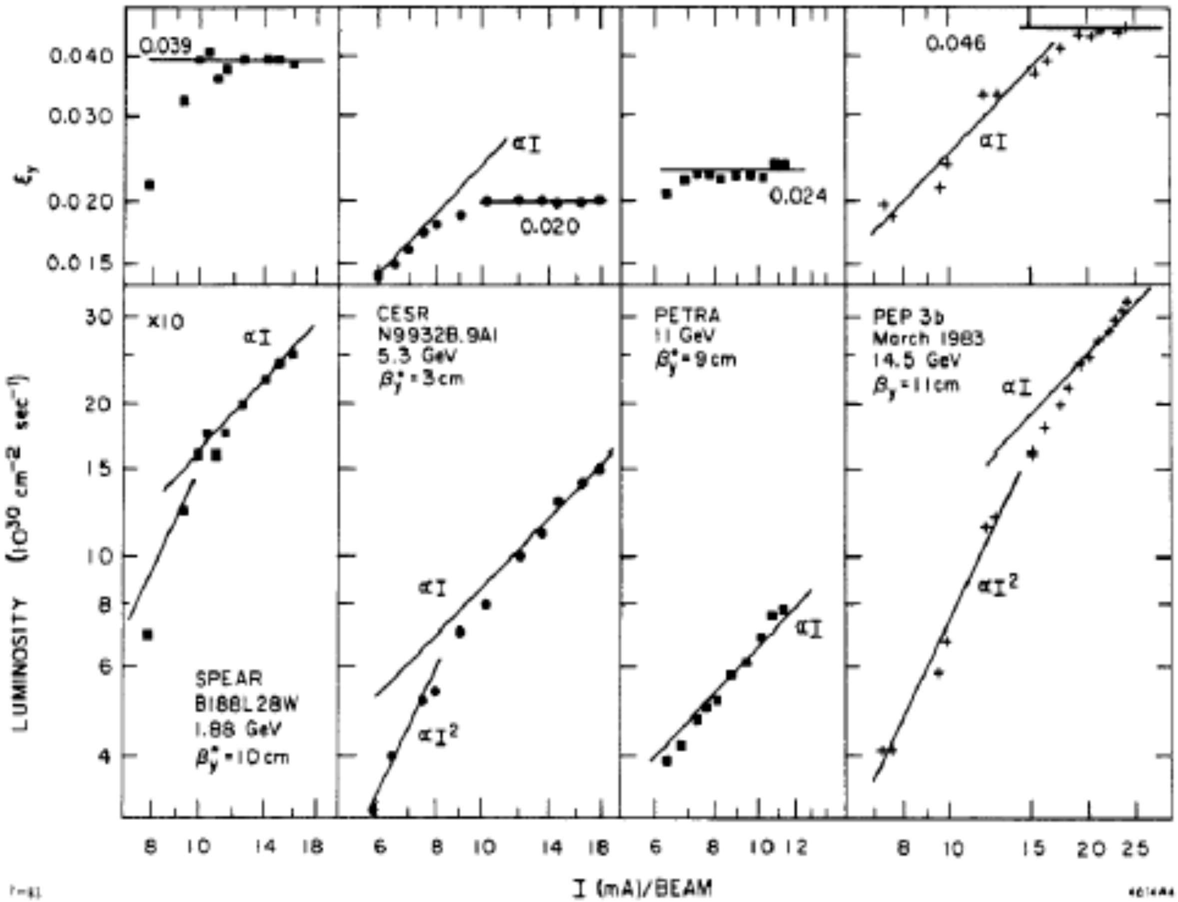
Increasing bunch population N_1 and N_2:

- luminosity should increase N_2 $\qquad L \propto N_1 N_2$
- beam-beam parameter linearly $\qquad \xi \propto N_{1,2}$

But…

Leptons beam-beam limit

First beam-beam limit (J. Seeman, 1983)



$\xi \propto const$

$\xi \propto N_{1,2}$

$L \propto N_{1,2}$

$L \propto N_1 N_2$

Luminosity and vertical tune shift parameter *vs*. beam current for SPEAR, CESR, PETRA & PEP.

What is happening?

$$\xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

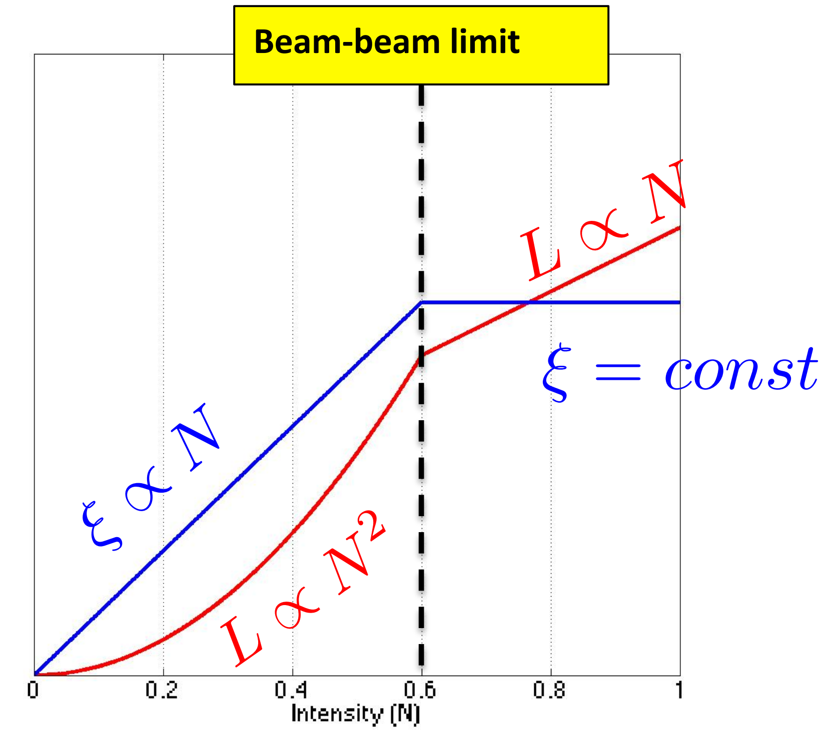
$$L = \frac{N^2 f n_b}{4\pi\sigma_x\sigma_y}$$

Lepton colliders $\sigma_x >> \sigma_y$

$$\xi_y \approx \frac{r_0 \beta^*_y}{2\pi\gamma\sigma_x} \cdot \frac{N}{\sigma_y}$$

$$L = \frac{N f n_b}{4\pi\sigma_x} \cdot \frac{N}{\sigma_y}$$

As to be constant!



Above beam-beam limit:
σ_y increases when N increases to keep ξ constant

Equilibrium emittance

1. Synchrotron radiation: vertical plane damped, horizontal plane exited!
2. Horizontal beam size normally much larger than vertical (LEP 200 - 4 μm)
3. Vertical beam-beam effect depends on horizontal (larger) amplitude
4. Coupling from horizontal to vertical plane

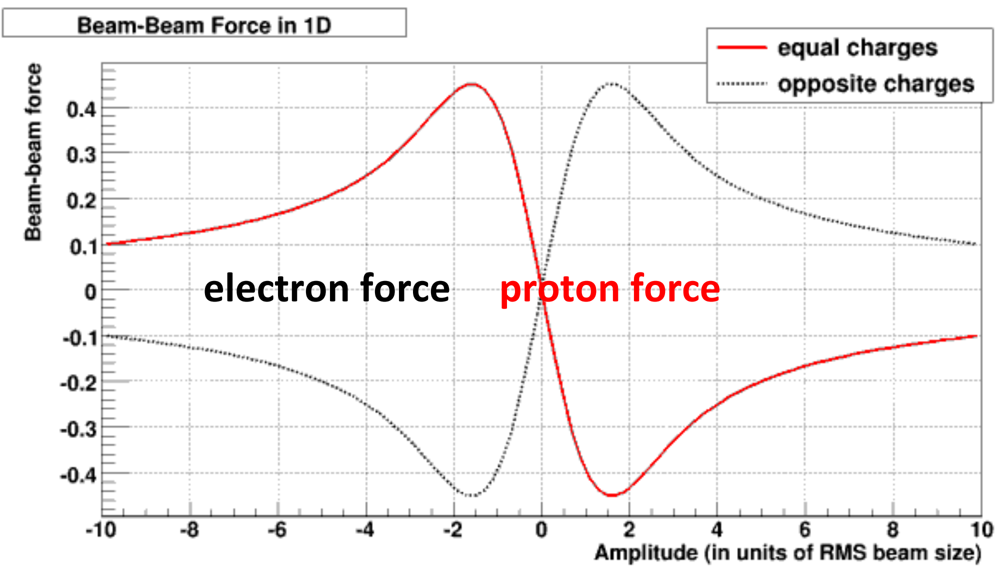
$$\xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

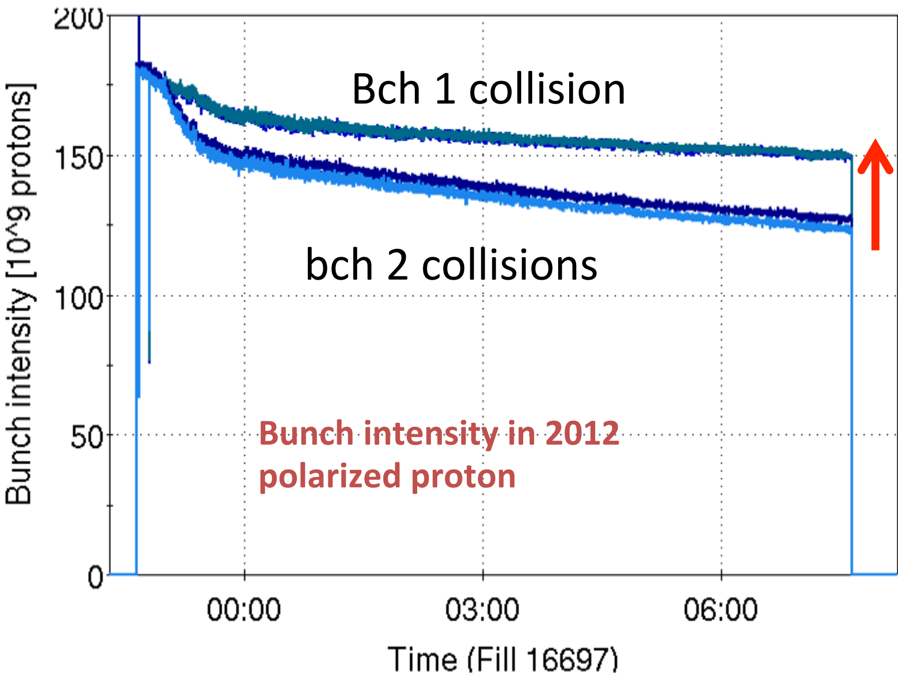
Equilibrium between horizontal excitation and vertical damping determines ξ_{limit}

Beam-beam compensation: Head-on

Head-on

- Linear e-lens, suppress shift
- Non-linear e-lens, suppress tune spread



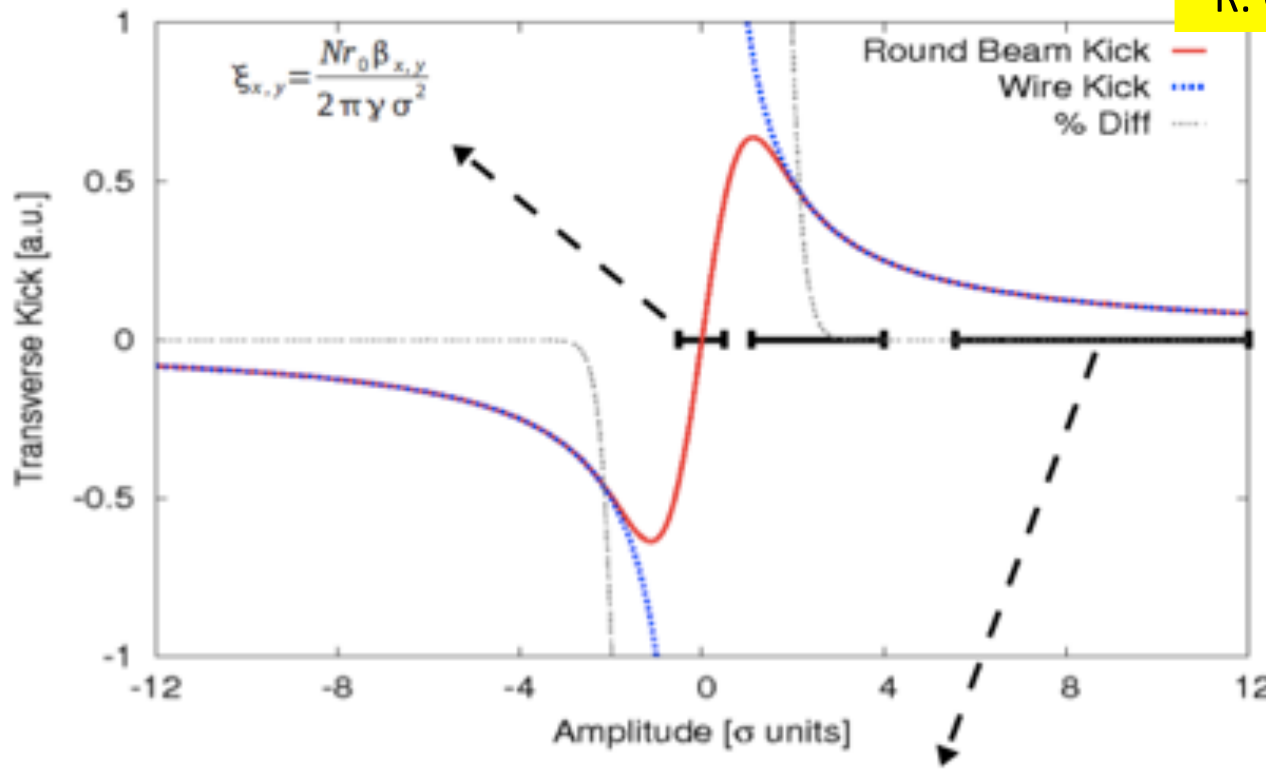


Past experience: at Tevatron linear and non-linear e-lenses, also hollow….
Recently proved and operationally used in RHIC! → 91% peak lumi increase!

Beam-beam compensations: long-range

Beam-beam wire compensation

R. Calaga



$\sigma << d$: $$\Delta x'(x,d) = -\frac{K}{d}.\left(1+\frac{x}{d}+\frac{x^2}{d^2}+\ldots\right)$$

- Past experiences: at RHIC several tests till 2009…
- **Present: prove of principle studies on-going for possible use in HL-LHC…**

…not covered here…

- *Linear colliders special issues*
- *Asymmetric beams effects*
- *Coasting beams*
- *Beamstrahlung*
- *Synchrobetatron coupling*
- *Beam-beam and impedance mode coupling*
- *…*

References:

[1] http://cern.ch/Werner.Herr/CAS2009/proceedings/bb_proc.pdf

[2] V. Shiltsev et al, "Beam beam effects in the Tevatron", Phys. Rev. ST Accel. Beams 8, 101001 (2005)

[3] Lyn Evans "The beam-beam interaction", CERN 84-15 (1984)

[4] Alex Chao "Lie Algebra Techniques for Nonlinear Dynamics" SLAC-PUB-9574 (2002)

[5] J. D. Jackson, "Classical Electrodynamics", John Wiley & Sons, NY, 1962.

[6] H. Grote, F. Schmidt, L. H. A. Leunissen,"LHC Dynamic Aperture at Collision", LHC-Project-Note 197, (1999).

[7] W. Herr,"Features and implications of different LHC crossing schemes", LHC-Project-Note 628, (2003).

[8] A. Hofmann,"Beam-beam modes for two beams with unequal tunes", CERN-SL-99-039 (AP) (1999) p. 56.

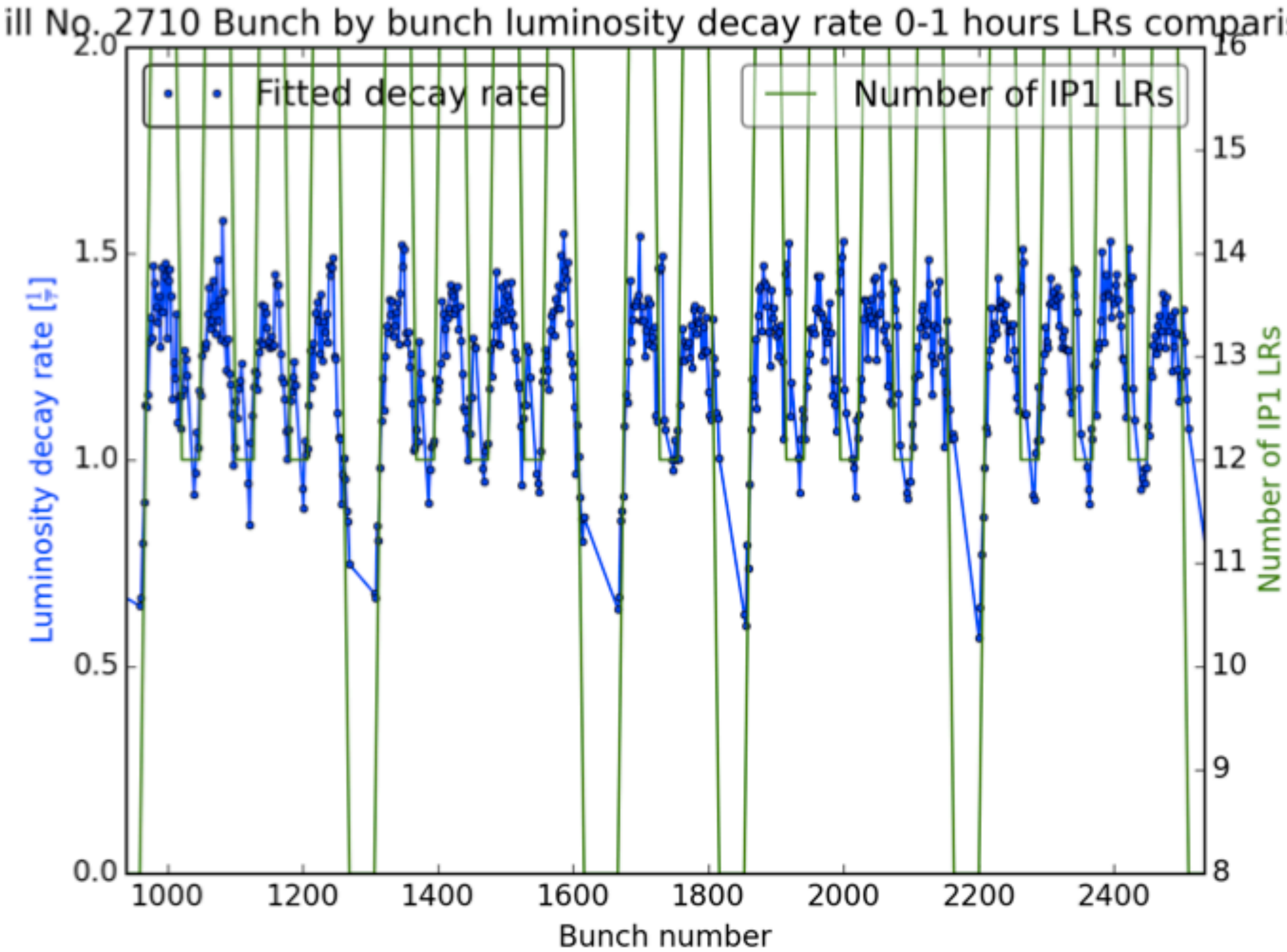
[9] Y. Alexahin, "On the Landau damping and decoherence of transverse dipole oscillations in colliding beams ", Part. Acc. 59, 43 (1996).

[10] R. Assmann et al., "Results of long-range beam-beam studies - scaling with beam separation and intensity "

…much more on the LHC Beam-beam webpage:

http://lhc-beam-beam.web.cern.ch/lhc-beam-beam/

Beam-beam Observations 2012 (I)



Strong Long-range effects →

Intensity lifetimes reduction → Higher losses

Emittance effects → increase of the transverse emittances and/or scraping

→ **Lumi lifetime reduction!**